Twenty Sixth Edition

Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS

ISC Konstanz Bifaciality: One small step for technology, one giant leap for kWh cost reduction

EMPA CIGS thin-film solar cells: Breakthroughs for further efficiency improvements

JA Solar R&D of mass-producible PERC cells with average conversion efficiency over 20%

ISFH Simplifying the fabrication of n-PERT solar cells: Recent progress at ISFH

Photovoltaics International Analysis of PV manufacturing expansions in 2014

Imec Adapting conventional tabbing– stringing technology for back-contact solar cells and modules

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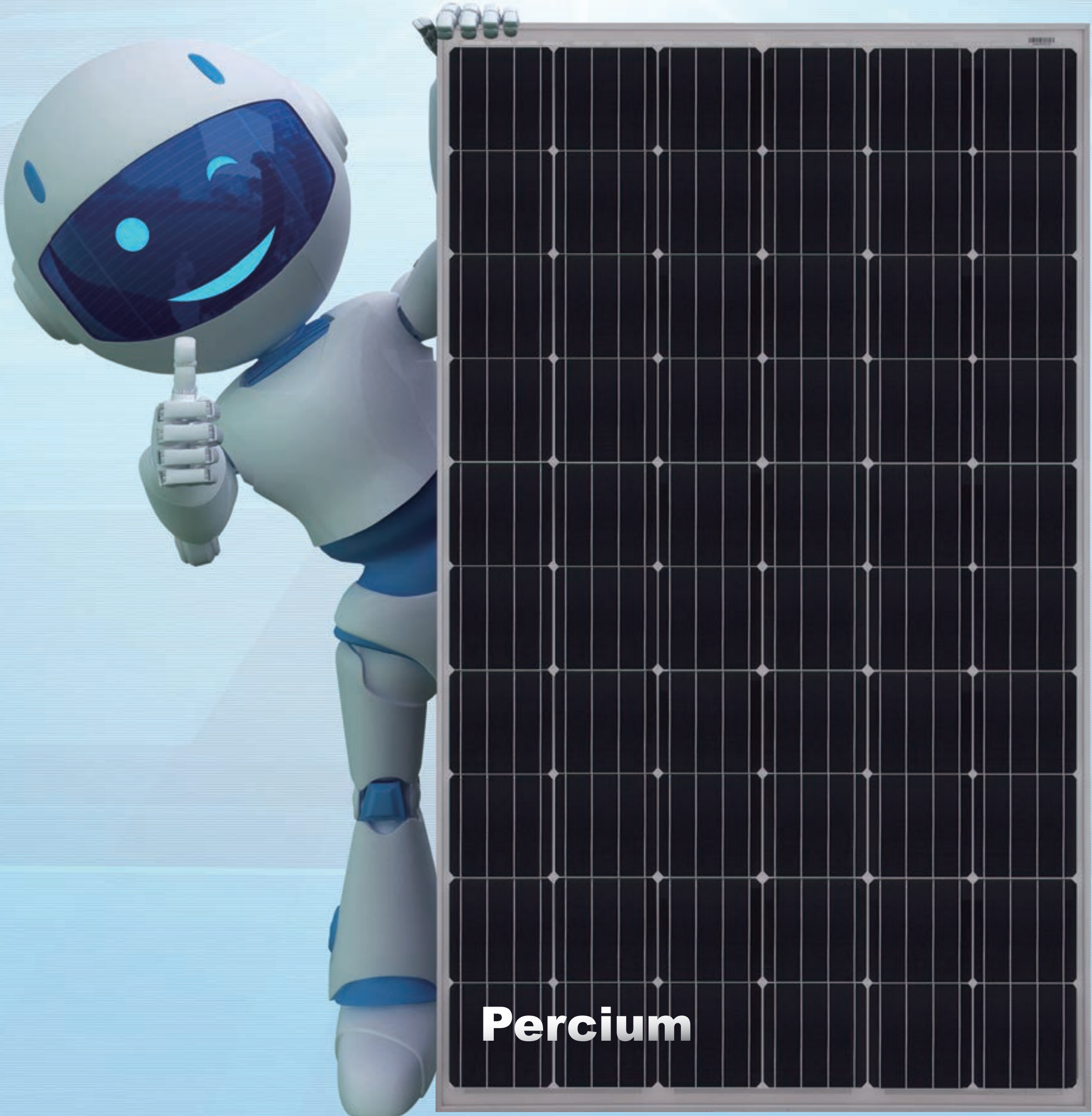

Harvest the Sunshine

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

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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,
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Foreword

Looking back, 2014 was a year of convalescence for a PV industry still battered and bruised from a period of ferocious competition. End-market demand continued apace, with analysts towards the end of 2014 predicting the year would see between around 45 and 50GW of deployment. That has begun to feed through to the supplier end of the market, with all the main manufacturers announcing capacity expansions in 2015 and further ahead.

Based on the latest available figures, it seems that that positive picture had yet to fully trickle down to the equipment manufacturers by the end of 2014. According to December 2014 figures published by SEMI, worldwide PV equipment billings and bookings both fell in the third quarter of 2014 by 17 and 33% respectively, leaving a below-parity book-to-bill ratio of 0.60. All these metrics are up on the same quarter last year, but down relative to previous quarters in 2014, suggesting a stumbling upstream recovery.

Nevertheless, the signs for 2015 are encouraging. In this issue of *Photovoltaics International*, we analyse the capacity expansions announced over the past 12 months. Mark Osborne's article on p.11 offers a detailed company-by-company breakdown of expansions in the pipeline, including fab locations and the technologies that will be produced.

One theme to emerge from this is that advanced cell technologies are starting to gain significant traction now, with a number of companies including n-type and PERC technologies in their future production line plans. That focus on new technologies is almost certain to harden as the upturn gathers pace and manufacturers look to take advantage of these advances in driving down kWh costs.

In this issue of *Photovoltaics International* we take a look at some of the other technologies that are coming to the fore. On p.32, the team at ISC Konstanz gives a detailed account of why bifaciality will become central in offsetting persistently high balance of system costs. Despite some criticisms of bifaciality as being an immature and excessively expensive technology, the authors maintain that it offers numerous benefits in driving down the levelized cost of energy in PV systems.

We also review the relative merits of mono- and multicrystalline cell technologies. On p.99, Solarbuzz analyst Finlay Colville weighs up why mc-Si looks set to remain the workhorse of the global PV end market, for the time being at least. But on p.21, researchers from LONGi Silicon in China give a timely reminder of why that could change as the kWh cost benefits offered by mono-Si come increasingly into play.

Not to be forgotten, the opportunities for CIGS thin-film to be a cost-competitive counterpart to crystalline silicon technologies are also explored in depth. A cutting-edge paper from the team at Switzerland's EMPA looks at how the potential for big efficiency gains in CIGS cells and the lower production costs of CIGS modules suggest, not to mention the opportunities for building-integrated applications, suggest a bright future for a technology that has never quite lived up to the hype.

I hope you enjoy this final issue of Photovoltaics International of 2014. I and the team would like to thank you for your ongoing support over the year and wish you a prosperous 2015.

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.

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News

DOE puts US$53 million into solar cost-cutting drive

The US Department of Energy (DOE) is to provide US$53 million to fund 40 research and development projects aimed at slashing the cost of solar. The funding was announced by energy secretary Ernest Moniz at Solar Power International in Las Vegas in October.

Among the beneficiaries of the funding, 10 research institutions will receive a share of US$14 million for RnD programmes aimed at improving the performance and efficiency of PV technologies. Another US$14 million will be invested through the DOE's Sunshot initiative in 20 projects exploring new ways to drive down the hardware and non-hardware soft costs of solar.

A further US$24 million will be awarded to 10 US-based solar manufacturers to develop new technologies to reduce costs and increase efficiency in manufacturing processes. These will focus on reducing cost in raw materials, labour-intensive processes and capital expenses.

Source: The White House

US government funding worth US$53 million will be awarded to various PV R&D projects.

New overseas fabs

Trina Solar to announce first overseas manufacturing plant 'soon'

Trina Solar is expected to announce its first PV manufacturing plant to be based outside China, although confirmation or details were not forthcoming at the time of going to press.

Company management has been negotiating with an unidentified third-party "strategic partner" to establish a joint venture manufacturing operation in Southeast Asia. Malaysia is a possible location for the plant, due to its low labour costs and established PV supply chain with a number of PV manufacturers operating large production facilities in the country.

Other overseas production expansions are also being evaluated for Trina, including production plants in the US and India.

Trina Solar has plans to take module capacity in 2015 to a range of between 4.8GW to 5GW, a similar rate of expansion as in 2014. However, wafer capacity is being held at 2014 levels of 1.7GW and solar cell production is only expected to increase 500MW to 3GW.

Hanwha SolarOne confirms 230MW South Korea module fab

Shortly ahead of the early December announcement of a merger with Hanwha Q CELLS, Hanwha SolarOne confirmed details of the new 230MW facility it plans to build in South Korea.

The new factory will be built in Eumseong, in central South Korea, and begin operation in the second quarter of 2015. It will cost US$30 million overall, with Hanwha SolarOne investing US$12 million in building the plant. The company said the factory would be used to meet local demand as well as the US market. The plant will employ around 200 people including a research and development team.

Hanwha Q CELLS to build 800MW module assembly plant in Malaysia

Hanwha Q CELLS announced in October plans to add four automated module assembly production lines to its existing main solar cell production facility in Cyberjaya, Malaysia.

The company will start construction of the 800MW fab expansion in early 2015. The new production lines are planned to be ready for first test production in the third quarter of 2015 and expected to reach full utilisation by early 2016. Financial details were not disclosed.

The greenfield expansion is the first to be announced from a tier-one PV manufacturer in several years, indicating strong demand expectations from the company in 2015 and beyond.

SunPower to assemble high-efficiency modules in South Africa

US PV energy provider, SunPower, has said it will own and operate a new module

Source: AE AMD

SunPower is expanding its module assembly capacity in South Africa, where it has been involved in PV projects such as Greefspan.

assembly plant in South Africa to produce its E20/440 high-efficiency PV panels.

The new plant, which will have an initial operational capacity of 160MW, is to be established in Cape Town and is set to be operational in 2015.

It will also be the headquarters for SunPower's engineering, procurement and construction, and operations and maintenance operations, consolidating its South African business into one building. SunPower said that around 150 new jobs would be created. The company already has a module assembly plant in Cape Town.

Italy's MegaCell to team on 120MW n-type mono cell plant in Egypt

Italian specialist solar cell manufacturer, MegaCell, has signed a memorandum of understanding with Egyptian investment firm, Misr Asset Management, to build and operate a 120MW solar cell and module assembly plant in Egypt using its n-type monocrystalline bi-facial cell technology.

The MoU specifies the manufacturing plant to be constructed in 2015, with MegaCell responsible for supplying equipment and technology transfer. MegaCell currently operates an 80MW production line in Italy, employing the 'BiSoN' cell technology developed at ISC Konstanz.

Capacity expansions

JA Solar to expand solar cell and module capacity by 20%

JA Solar is planning to expand both solar cell and PV module capacity by around 20%, in order to keep in alignment with expected global market growth in 2015.

The company reported higher than expected shipments and revenue for the third quarter of 2014, saying capacity was fully booked in the fourth quarter and that it expected strong demand in the first quarter of 2015. JA Solar noted that around 75% of planned production was already booked for the first quarter.

JA Solar had previously said it was aiming to increase capacity of solar cells and modules to 2.8GW each in 2014, up from 2.5GW and 1.8GW respectively from 2013.

JinkoSolar planning up to 25% module capacity expansion in 2015

Citing continued strong global growth and market share gains, major PV manufacturer JinkoSolar has said it is planning to expand module capacity in 2015 by 20% to 25%. Solar cell capacity, which had stood at 1.5GW at the end of 2013, was expanded to 1.8GW in the third quarter of 2014 and was on track to reach its target of 2GW by year-end.

PV module capacity was Jinko's key expansion target in 2014, with previous guidance pushing capacity to 3GW by year-end. However, the company guided full-year 2014 PV module shipments to be in the range of 2.9GW and 3.2GW, with the high point of guidance ahead of capacity.

STR seeing growing PV module assembly in Malaysia after US anti-dumping case

PV module encapsulant material producer, STR Holdings, has expanded production at its Malaysian plant to meet growing PV module production in the country after the latest round of US anti-dumping duties on Chinese and Taiwanese made solar cells.

STR's Malaysia facility was going to be ramped down as part of its restructuring efforts to reduce costs and return to profitability.

However, Joseph Radziewicz, CFO of STR Holdings said in the company's third quarter earnings call that it had "incurred additional cost to scale this facility back up". "In November, we achieved certification with a potential new significant customer for this facility," he added.

STR is also ramping up its first encapsulant material production line in Suzhou, China.

Manufacturing in the Americas

Solar module manufacturing expansion plans in US near 2GW

A number of recent announcements from US-based solar PV manufacturers have been made recently concerning new or expanded module capacity with, 10 companies have announced current plans that would add close to 2GW of new capacity in the US. Close to half of the new capacity is expected to come online in 2015.

This is in stark contrast to the position in 2011, when more than 20 US-based PV module manufacturers (predominantly thin-film producers) went bankrupt through 2012. The wave of new capacity expansion announcements kicked off in June 2014, with the major 1GW production plans of SolarCity, continuing through to November with First Solar planning to add two new CdTe thin-film lines at its facility in Perrysburg, Ohio, boosting capacity by an estimated 178MW.

Schmid constructing integrated PV production plant in Argentina

PV equipment and technology specialist, Schmid Group, officially started construction of an integrated PV production plant in Argentina for the provincial government of San Juan in early November.

An estimated 2,000 people were said to have attended a ground-breaking ceremony for the 71MW production plant, which was said to include ingot/wafer and solar cell/module production.

The other key partners in the project include energy provider, Energia Provincial Sociedad del Estado (EPSE) and the Universidad Nacional de San Juan, both based in San Juan. The integrated production plant was first touted in March 2013, when EPSE announced a letter of intent with Schmid.

The planned plant was estimated at the time to have a cost of around US$100 million and was slated for operation by the end of 2014. Fabrication of the first modules is scheduled for 15 October 2015.

German consortium evaluating major PV manufacturing hub in Brazil

An ad hoc consortium of three German research institutes and the south-western German industry association, Solar Cluster, is undertaking a detailed feasibility study for the establishment of a fully integrated PV manufacturing facility on behalf of ITAIPU, a Brazilian-Paraguayan power company, and FIEP, an industry association.

The feasibility study includes the construction of a 10,000MT polysilicon plant and integrated wafer, cell and module production capacity of 680MW.

Significantly, the location being evaluated for the project is Paraná, near the 14GW Itaipu hydropower plant. This would potentially provide the lowest cost electricity source in particular for the polysilicon plant, but also reduce carbon emissions from the manufacturing of the PV modules.

Yingli Green to partner on module assembly plant in Brazil

Latin America has become Yingli Green's key near-term focus as an emerging market, with plans to partner in Brazil to operate a PV module assembly plant.

Speaking in late October, Robert Petrina, vice president of sales and managing director of Yingli Green America, said that servicing key markets of Chile, Mexico and Brazil had become a "commitment" of the company.

Brazil's national development bank, BNDES, has included new local content requirements for solar projects to access very low interest rate project finance

Source: SolarWorld

SolarWorld plans to expand its production line in Oregon.

in reverse (LER) auctions for PV. To be competitive and a chance of winning bids in Brazil, module assembly at least would be required.

SolarWorld to spend US$10 million on PERC cell/module expansion in Oregon

SolarWorld plans to invest over US$10 million in adding a new 'flexible' manufacturing line at its Hillsboro, Oregon facility with the creation of around 200 jobs.

Mukesh Dulani, US president of SolarWorld said in October that "SolarWorld was growing again". SolarWorld will expand module capacity from 390MW to 530MW, with completion and ramp by the third quarter of 2015.

Key to the expansion is the further investment in ramping PERC cell and module capacity, providing modules with around 280Wp performance. Around 25 jobs would be created in the first quarter of 2015, specifically for PERC cell production expansion of 100MW. In the second quarter more jobs would be created for the initial start of the expanded module production.

The US$10 million-plus investment brings SolarWorld's cumulative investment in the Hillsboro plant to around US$630 million.

Company news

ReneSola accepted into Intertek's Global 'SATELLITE' programme

The PV module testing laboratory of China-based PV manufacturer, ReneSola has been qualified to join testing firm Intertek's Global 'SATELLITE' programme.

Key benefits of the Intertek system is that it provides manufacturers with potentially shorter product development cycles through coordinated testing and certification processes.

"By joining the SATELLITE programme, we can better coordinate testing and certification with our product development cycles, which should not only reduce our overall testing costs but also shorten the time needed to take our products to market," said Dr. Bill Hou, director of ReneSola's product centre.

ReneSola's Jiangsu Product Centre Laboratory in China had to be evaluated and certified by Intertek. The entry to the program should also shorten Intertek's ETL certification processes for the company.

Mondragon Assembly acquires rival

PV module assembly equipment specialist, Mondragon Assembly, has acquired rival Spanish firm, Gorosabel Group's solar assembly and automation business unit.

Mondragon Assembly and Gorosabel had been key players with similar market share of the module assembly equipment sector and had competed on a global basis.

Mondragon Assembly said the acquisition would add the "knowledge and experience of a remarkable competitor, along with its client portfolio and broad range of products". As a result the company would be improving its technology and business opportunities in the development of solar module assembly lines.

The company said it would boost the development of new products in the Gorosabel range while offering technical support and repair services to the equipment already installed around the world.

Source: Mondragon

Mondragon has acquired Gorosabel's assembly and automation unit.

Analysis of PV manufacturing capacity expansion plans in 2014

Mark Osborne, Senior News Editor, *Photovoltaics International*

ABSTRACT
Global PV end-market demand for PV modules is expected to reach around 50GW in 2014, which has prompted the need for manufacturers to expand capacity to meet demand. With effective module capacity standing at around 45GW at the end of 2013, *Photovoltaics International* (PVI) has analysed solar cell, c-Si and thin-film capacity expansion announcements that were extensively reported by sister website, PV Tech, from the beginning of 2014 through to the end of November to establish key trends.

Next capacity expansion phase

After two years of chronic overcapacity, 2014 has heralded an end to profitless prosperity for most of the major PV manufacturers and the beginning of the next technology buy cycle and meaningful capacity expansion phase, according to the latest analysis of capacity expansions announced by the manufacturers of solar cells and PV modules, including thin-film variants, in 2014.

> "2014 has heralded an end to profitless prosperity for most of the major PV manufacturers and the beginning of the next technology buy cycle and meaningful capacity expansion phase."

Source: Hanwha Q CELLS.

Figure 1. Hanwha Q CELLS is increasing its module production capacity in Malaysia in 2015.

In tandem with strong end-market demand that exceeded effective manufacturing capacity by the end of 2013, the first quarter of 2014 (Fig. 2) ushered in combined solar cell and PV module capacity expansion announcements totalling almost 6.8GW. This was followed by a further 4.5GW of capacity expansion announcements in the second quarter of 2014. The third quarter proved to be the least active quarter of the year: only 1.4GW of new capacity expansions were announced. But with 5.9GW announced in October and November, the fourth quarter had already easily surpassed the scale of capacity announcements in the second. During the 11 months analysed, a total of around 18.6GW of new capacity was announced.

Fig. 3 shows that c-Si module-assembly capacity expansion announcements dominated in the first quarter of 2014, totalling over 4GW. This was followed by over 1.2GW of c-Si solar cell expansions and just over 1GW of thin-film capacity expansion plans. However, in the second quarter of 2014, over 2.7GW of c-Si solar cell expansion plans had been announced, compared with a further 1.8GW of c-Si module expansions. Only 100MW of new thin-film activity occurred during the quarter.

With the third quarter having by far the least activity, only around 830MW of c-Si module, 600MW of c-Si cell and 75MW of thin-film capacity expansions were announced. The fourth quarter (October and November) recovered strongly, as indicated by at least a further 4GW of c-Si module-assembly capacity expansion announcements, followed by c-Si cell expansions totalling over 2.1GW, and thin-film expansions of over 500MW. In 2014 total new thin-film capacity expansion announcements are therefore estimated to have been around 1.7GW, while c-Si solar cell topped 6.7GW and c-Si module-assembly capacity expansion announcements exceeded well over 10GW (Fig. 4).

Crystalline PV module capacity expansions

As Table 1 shows, there were around 30 companies announcing c-Si module capacity expansions, totalling around 10GW, in 2014. Not surprisingly, a large number of capacity expansion announcements occurred in the first quarter of 2014 (amounting to 4GW). This is primarily due to stock-market-listed companies typically providing full-year financial guidance and details of any production expansion plans when supplying fourth-quarter

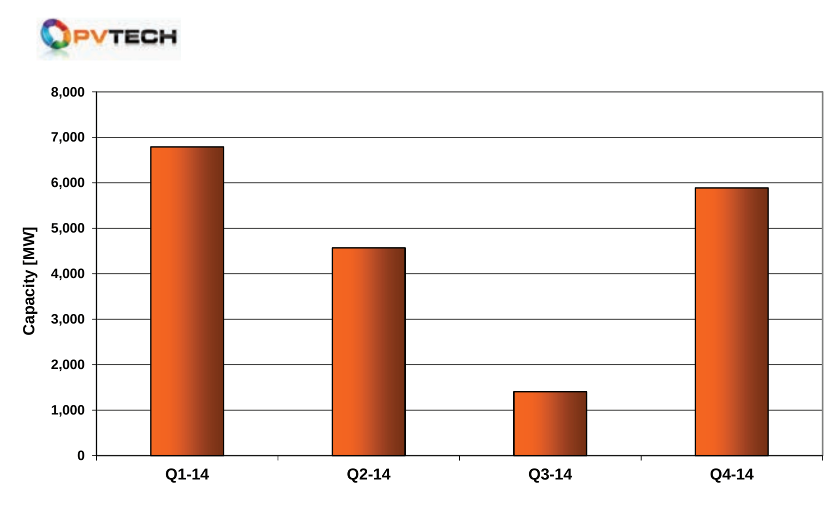


Figure 2. Cell/module manufacturing capacity expansions announced in 2014 by quarter (to end-November).

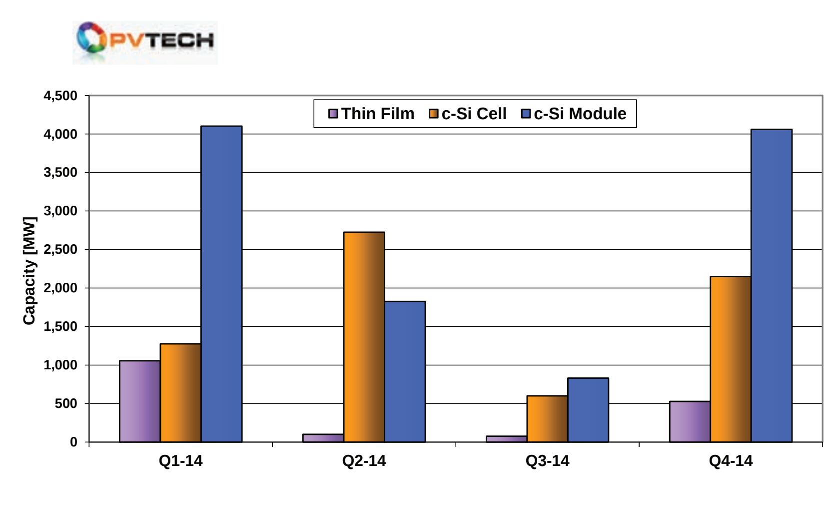


Figure 3. Capacity expansion announcements in 2014 by product type quarterly.

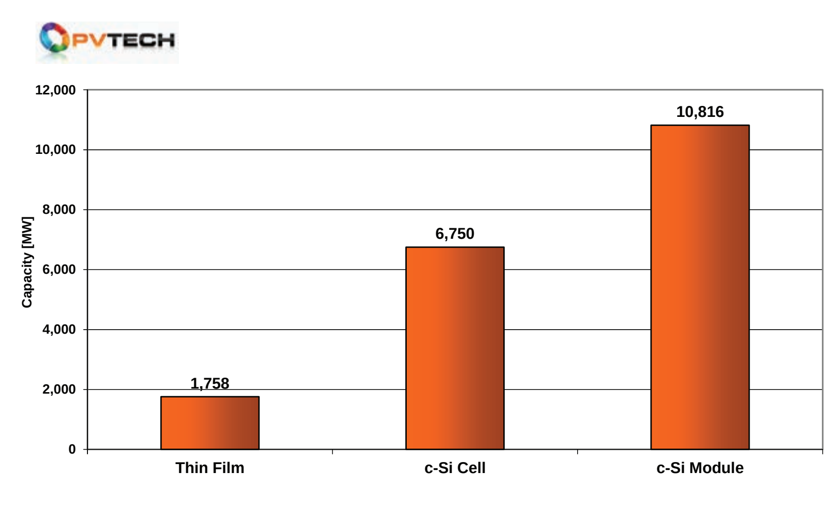


Figure 4. Total capacity expansion announcements in 2014 by product type.

and full-year financial results for the previous year in that quarter.

Three companies – Wuxi Suntech, Trina Solar and JA Solar – announced the largest module-assembly plans in the first quarter, all at 1GW. There have been no other companies in the first 11 months of the year that have announced expansions to this level.

However, in the fourth quarter of 2014, six tier-one module manufacturers – Hanwha Q CELLS, SunPower, Canadian Solar, JA Solar, Hanwha SolarOne and again JinkoSolar – announced module-assembly expansion plans that would be implemented in 2015. This indicates that measured capacity expansions that began in 2013 and went through the first half of 2014 were insufficient to meet end-market demand.

“Six tier-one module manufacturers announced module-assembly expansion plans that would be implemented in 2015.”

A good example of this comes from JinkoSolar, which had been one of the few companies that expanded capacity in 2013 and announced expansion plans in the first quarter of 2014. In November 2014 the company said that it planned to further expand capacity by around 20% in 2015, matching what it believed to be the overall growth of end-market demand that year. Full details of its 2015 expansion plans will be revealed in the first quarter of 2015, as expected, but guidance given indicates further capacity expansion of between 600 and 800MW can be expected.

JinkoSolar actually expanded module production a further 200MW than previously guided at the beginning of the year. This is because the company has been gaining market share on the basis of its claiming to be the lowest-cost producer and had guided module shipment growth of 65 to 82% compared with 2013, resulting in module shipment guidance of 2.9GW to 3.2GW in 2014. The company is expected to become the third largest in 2014, ranked by shipments, up from being ranked fifth in the previous year.

As Table 2 shows, there are five top-10 ranked module suppliers that have guided significant PV module shipment growth in 2014 – Trina Solar, Canadian Solar, JinkoSolar, ReneSola and JA Solar. When those companies

	Company	Shipments [GW]	Growth [%]
1	Yingli Green	3.2	3–4.6
2	Trina Solar	2.58	40–42
3	Sharp Corp.	2.1	(9–5)
4	Canadian Solar	1.894	45–48
5	JinkoSolar	1.765	65–82
6	ReneSola	1.728	38–45
7	First Solar	1.6	12–19
8	Hanwha SolarOne	1.280	10–15
9	Kyocera	1.2	0–17
10	JA Solar	1.173	105–114

Table 1. Top 10 PV manufacturers guided shipment growth for 2014 (Q3-14 guidance).

are compared with capacity announcements in the first quarter, a direct correlation becomes evident.

However, the fastest-growing company in the top-10 list from 2013 is the company that was ranked 10th – JA Solar. It has guided module shipment growth in the range 105 to 114% in 2014, while guiding shipments of between 2.4 and 2.5GW. Not only is the growth rate remarkable and clearly the highest of all top-10 ranked producers, but also just a few years ago the company was primarily a merchant solar cell producer. Shifting to become predominantly a module supplier has proved to be a huge success and the company is seriously challenging to become a top-5 ranked supplier in 2014.

ReneSola, on the other hand, has adopted a strategy of expanding outsourced manufacturing; however, it has had two of its OEM partners – Jabil Circuit and Vitec Global Solar – add capacity in 2014 (Table 2) to meet its shipment guidance and demand requirements. This therefore indicates that all five of the shipment growth leaders have closely matched supply with demand in 2014 and are expected to follow a similar path in 2015.

Interestingly, when Tables 1 and 2 are compared, the largest PV manufacturer – Yingli Green – is guiding almost zero shipment growth in a boom year and did not announce any new capacity expansions in 2014.

Another interesting trend seen in Table 2 is the number of announcements from emerging markets, such as Latin America and Africa, as well as from other new entrants that are selecting alternative module-assembly technology to provide them with a differentiated product. These trends are also expected to gain momentum in 2015 and beyond.

Crystalline solar cell capacity expansions

As Table 3 shows, there were 12 companies that announced dedicated c-Si solar cell capacity expansions in the first 11 months of 2014. Although c-Si module-assembly expansions significantly outweighed solar cell expansions overall, the latter have been significant and occurred throughout the year.

The biggest expansion was announced by Canadian Solar in a joint venture deal with GCL-Poly. However, in line with its significant shipment growth, JA Solar announced two large solar cell expansions in 2014, totalling 900MW. Not surprisingly, the majority of large capacity expansions were related to high-efficiency multi c-Si solar cells and PERC cell design technology.

Overall, dedicated c-Si solar cell expansions of around 4GW represent a massive improvement on the two previous

Company	Announcement date	Manufacturing location	New nameplate PV module capacity [MW]	Production/product type
Jinko Solar/Topoint	Jan-14	China	100	multi c-Si module assembly
JA Solar/Powerway	Jan-14	Port Elizabeth, South Africa	150	multi c-Si module assembly
ELIFRANCE	Feb-14	La Talaudière, France	20*	multi c-Si module assembly
EL.ITAL	Feb-14	Avellino, Italy	20*	multi c-Si module assembly
Pure Energy Generation	Feb-14	Marechal, Brazil	70	multi c-Si module assembly
Wuxi Suntech	Feb-14	Wuxi, China	1000	multi c-Si module assembly
REC Solar	Feb-14	Singapore	120	multi c-Si module assembly
Vitec Global Solar	Mar-14	Otawara City, Tochigi Prefecture, Japan	80	multi c-Si module assembly
Trina Solar	Mar-14	China	1000	multi c-Si module assembly
Canadian Solar	Mar-14	China	400	multi c-Si module assembly
JA Solar	Mar-14	China	1000	c-Si module assembly
Jabil Circuits	Apr-14	Kwidzyn, Poland	240	multi c-Si module assembly
REC Solar	Apr-14	Singapore	300	multi c-Si module assembly
Solargiga/Jinzhou Yangguang	Apr-14	China	170	mono c-Si module assembly
Hanwha SolarOne	May-14	China	500	multi c-Si module assembly
Green Panel Technology	May-14	Tunis, Tunisia	30	multi c-Si module assembly Jurawatt Tunisie
Tata Solar	May-14	Bangalore, India	75	c-Si module assembly
Hanplast	Jun-14	Poland	85	Meyer Burger's SmartWire module assembly
Gintung Energy	Jun-14	Taiwan	150	c-Si module assembly
Kyocera	Jun-14	Japan	200	c-Si module assembly
Suniva	Jul-14	Saginaw, Michigan, USA	200	n-type mono module assembly
BYD	Jul-14	Sao Paulo, Brazil	20*	c-Si module assembly/R&D
Tecnova Renovables/Sky Solar	Aug-14	Paysandú, Uruguay	50	c-Si module assembly
Grupo IUSA	Sep-14	Mexico	50–200	c-Si module assembly
SolarTech	Sep-14	Riviera Beach, Florida, USA	80+	Meyer Burger's SmartWire module assembly
Hanwha Q CELLS	Oct-14	Cyberjaya, Malaysia	800	c-Si PERC/module assembly
SunPower	Nov-14	Cape Town, South Africa	160	n-type mono module assembly
Canadian Solar	Nov-14	Changshu and Luoyang plants, China	500	mono/multi c-Si PERC modules
JA Solar	Nov-14	China	600	multi c-Si module assembly
Hanwha SolarOne	Nov-14	South Korea	250	multi c-Si module assembly
JinkoSolar	Nov-14	China	200	multi c-Si module assembly
JinkoSolar	Nov-14	China	640–800	c-Si PERC/module assembly

* Estimated

Table 2. Dedicated c-Si module capacity expansion announcements in 2014.

Company	Announcement date	Manufacturing location	New nameplate PV module capacity [MW]	Production/product type
Hanwha Q CELLS	Jan-14	Cyberjaya, Malaysia	204	c-Si PERC cell
Jinko Solar/Topoint	Jan-14	China	500	multi c-Si cell
Solland Solar	Feb-14	Heerlen, Holland	50	multi c-Si cell
Trina Solar	Mar-14	China	500	multi c-Si cell
JA Solar	Mar-14	China	300	c-Si cell
Hanwha SolarOne	May-14	China	200	c-Si cell
Canadian Solar/GCL-Poly	May-14	Funing, Jiangsu Province, China	1200	c-Si cell
Indosolar	Jun-14	India	250	multi c-Si selective emitter cell
Shaanxi Youser	Jul-14	China	380	multi c-Si cell
Hareon Solar	Sep-14	China	100*	c-Si PERC cells
TS Solartech	Sep-14	Malaysia	20*	multi c-Si cell
Canadian Solar	Nov-14	Funing, China	400	mono c-Si PERC cell
JA Solar	Nov-14	China	600	multi c-Si solar cell

* Estimated

Table 3. C-Si solar cell capacity expansion announcements in 2014.

Company	Announcement date	Manufacturing location	New nameplate PV module capacity [MW]	Production/product type
Ascent Solar	Jan-14	Suqian, Jiangsu Province, China	25	Flex CIGS thin film
Solar Frontier	Jan-14	Tohohu, Japan	150	CIS thin film
Hanergy Solar	Jan-14	Caofeidian, Hebei Province, China	600	CIGS thin film
TSMC	Feb-14	Taiwan	80	CIGS thin film
First Solar	Mar-14	Malaysia	200	CdTe thin-film upgrades
Stion Corp.	Jun-14	Hattiesburg, Mississippi, USA	100*	CIGS thin-film module assembly
Siva Power	Jul-14	Silicon Valley, California, USA	CIGS pilot line	CIGS thin-film pilot line
SoloPower	Jul-14	Portland, Oregon, USA	75	Flex CIGS thin film
First Solar	Nov-14	Perrysburg, Ohio, USA	178	CdTe thin-film modules
First Solar	Nov-14	Malaysia	350	CdTe thin-film module lines upgraded and recommissioned

* Estimated

Table 4. Thin-film capacity expansion announcements in 2014.

years of chronic overcapacity and underinvestment. The trend may still be to underinvest in solar cell capacity, because of the availability of capacity from large merchant suppliers and higher capital expenditure requirements for new cell lines than for module assembly; however, there are still a number of tier-one suppliers that have yet to make any cell capacity expansion announcements.

Thin-film capacity expansions

Table 4 shows that thin-film announcements were limited in both scale and the number of companies, reflecting the overall decline in thin-film manufacturers over the last few years. Nevertheless, the table shows that the sector still has some life and that, after several cuts to its nameplate capacity, First Solar is planning to recommission idled lines as well as adding a small amount of new capacity in 2015.

One company to watch is Hanergy Solar, which has bold plans to become the leading thin-film firm. But it must focus on ramping up its first wave of new capacity expansions before it is clear that even the 600MW of new capacity can be classified as effective capacity. Other activity is focused on much smaller players, and lack of transparency in these

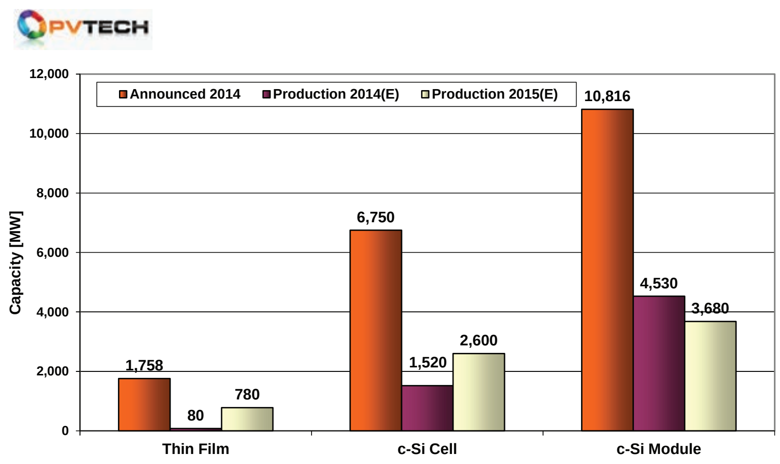


Figure 5. Capacity expansion announcements compared with estimated (E) new production online in 2014.

announcements requires a conservative approach as to when and if such capacity will come on stream.

New capacity expansion announcements vs. online conversion

The key aspect of plotting new capacity announcement is to understand the impact that capacity will eventually have on effective capacity figures. Fig. 5 accounts for announced capacity expansions that are both believed to have come online in 2014 and expected to come online in 2015.

Clearly, not all the expansions announced in 2014 are expected to materialize as meaningful effective capacity in 2015. There are several key reasons for this. First, several large capacity expansions announced in 2014 are unlikely to see the light of day next year. For example, the 1GW fab planned by SolarCity only broke ground in the fourth quarter of 2014, indicating that – with construction, pilot production and an expected slow ramp-up because of the complexity of high-performance n-type mono cells – the integrated (cell/module) capacity will most likely not be online until 2016 and will then ramp up from there.

Also keeping executions lower than would be expected is the 1GW module expansion planned by Wuxi Suntech. Lack of updated information on those plans since the early part of the year, coupled with recently guided module shipments, suggests capacity expansions have yet to take place.

New entrants also play a part in new capacity, but they have historically taken longer to bring new facilities online than, say, tier-one producers; this impacts in particular both c-Si and thin-film start-ups. With several new module-assembly companies (such as Hanplast) planning on adopting new assembly technology, and new entrants simply emerging with integrated cell/module lines (such as ViaSolis), a lower ramp-up rate has also been factored into the figures.

Fig. 5 shows that over 4GW of module-assembly capacity, primarily by major players, was estimated to have come online in 2014, contributing to a meaningful but measured increase in effective capacity in the year.

Fig. 5 also shows that around 1.5GW of the 6.7GW of c-Si solar cell capacity announced in 2014 came online in the same year. Lead times for cell equipment are longer than for module equipment, but the majority of cell equipment installs in 2014 came from announcements in the first quarter, with only a small element being announced in the second quarter. However, second quarter c-Si cell expansions were dominated by the SolarCity announcement, which is not expected to convert to meaningful effective capacity until 2017. Therefore, a further 3.68GW of effective c-Si solar cell capacity is estimated to come on stream from 2014 announcements in 2015. The higher levels expected in 2015 also reflect the need to add cell capacity, which has significantly lagged effective module capacity since 2013.

With the expected effective capacity additions in 2015 by thin-film leader, First Solar, and nearest rival, Solar Frontier, the overall effective online PV module capacity is expected to be in the region of 4.5GW, in line with capacity added in 2014 from announcements. This does not, however, take into consideration expected new capacity announcements from tier-one suppliers in the first quarter of 2015, indicating that effective module capacity coming online in 2015 will be much higher than what was achieved in 2014.

> "Tracking new capacity announcements in 2015 will be essential to visualizing whether the industry retains a measured approach to expansions or reverts to over-exuberance."

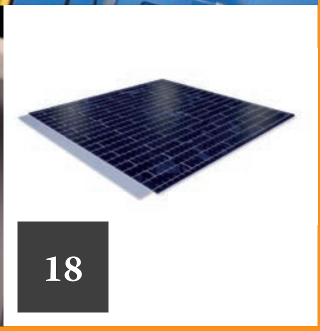
Conclusion

As shown in this paper, there has been a good recovery in PV capacity expansions in 2014, which have been measured to global demand growth. A number of major tier-one suppliers have benefited the most, with strong shipment growth projections mirroring their capacity expansion announcements. C-Si solar cell capacity has also increased and is expected to increase further in 2015. Advanced n-type cell expansions are also under way and are expected to gain further momentum in 2015.

Next year is expected to see higher levels of new capacity come online than in 2014, yet there is little evidence to suggest that this will be large enough to cause concern over the building-up of the next overcapacity phase. Indeed, should end-market demand growth projections of over 60GW be realized in 2015, more than 15GW of new capacity would need to be in place by year end to cause real concern in 2016.

Tracking new capacity announcements in 2015, especially in the first quarter, will therefore be essential to visualizing whether the industry retains a measured approach to expansions or reverts to over-exuberance.

Materials



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Five reasons to choose mono-Si

Strategy and Planning Department, LONGi Silicon Materials Corp., Xi'an, China

Wafer demand exceeding supply, says GCL-Poly as FBR technology ramps

GCL-Poly Energy Holdings, the largest polysilicon and solar wafer producer reported strong third quarter results as demand exceeded supply and was running at 100% utilization rates for both products.

The company reported that polysilicon production at a record high of 5,800MT per month, resulting in production of 17,241MT in the third quarter, representing an increase of approximately 27.2% compared with 13,550MT over the same period of last year. GCL-Poly sold approximately 11,077MT of polysilicon in the first three quarters of 2014, representing a decrease of approximately 11.3% compared with 12,490MT over the same period of last year as in-house wafer demand increased significantly.

GCL management said production of granular FBR (Fluidized Bed Reactor) polysilicon had commenced in the third quarter of 2014 and the company had ramped its first reactor, noting that production had been progressing well to the point that it exceeded expectations, both in terms of cost and technology.

GCL-Poly said that wafer production reached 3,681MW in the third quarter of 2014, compared with 2,546MW in the prior year period, a 45% increase. Wafer production volume for the first three quarters of 2014 was approximately 9,584MW (including tolling of around 400MW), representing an increase of approximately 59.8% compared with 5,998MW in the prior year period.

The company sold approximately 3,620MW of wafers in the quarter with an ASP of US$0.21 per watt, compared to US$0.22 per watt last year.

Source: Trina Solar

Demand for GCL polysilicon and wafers is outstripping supply.

Capital losses and bankruptcy

GET mulling overseas production as sales fall

Taiwan-based solar wafer producer, Green Energy Technology (GET), reported sales in November of NT$1,460 million (US$46.79 million), down 5.6% on the previous month. GET sales have recovered strongly since June and the company has retained production utilisation rates above 95%. Sales reached a new peak of US$49.59 million in October.

The company noted in a financial statement that it was awaiting the final US anti-dumping decision before making a decision over locating a manufacturing plant overseas, supported by its parent company, Tatung Group. GET currently has multicrystalline ingot/wafer production plants in both Taiwan and China totalling 2GW.

Comtec Solar revenue falls steeply in Q3

N-type monocrystalline wafer producer, Comtec Solar Systems Group, has reported a steep decline in revenue for the third quarter of 2014. Comtec reported third quarter revenue of RMB158.9 million (US$ 25.89 million), compared to US$46.28 million in the previous quarter.

The company reported an unaudited consolidated gross profit of RMB11,781,000 (US$19.19 million) and a net loss of RMB5,291,000 (US$8.6 million). Comtec said it had applied diamond wire saws to its slicing process, which further improve the manufacturing efficiency of its China facilities, and planned to use diamond wire saws at its production facility in Malaysia.

Taiwan Polysilicon Corp enters bankruptcy protection

Taiwan Polysilicon Corp has filed for corporate restructuring after a court ruled that it had failed to fulfil its obligations on NT$940 million (US$30.6 million) bonds. In a statement to local press, the company's president, Wu Shian-jin, said that the filing would allow the company to hold onto its manufacturing assets so that it can reap the benefits once the price of polysilicon recovers.

GCL-Poly bails out Chaori Solar and plans to dispose of wafer business

The largest polysilicon producer, GCL-Poly Energy Holdings, and a group of other investors are to take a majority shareholding in bankrupt PV module manufacturer, Shanghai Chaori Solar.

GCL-Poly said in a financial statement that a restructuring plan had been approved by the creditors of Chaori Solar on 23 October 2014 and the Shanghai Municipal First Intermediate People's Court on 28 October 2014.

SPI 2014: Sapphire yield issues brought GTAT down

GT Advanced Technology (GTAT) was suffering from sapphire yield issues at its Arizona production plant, according to a consensus of financial analysts and equipment suppliers that PV Tech spoke to during Solar Power International, held in Las Vegas in October.

GTAT had been booked to exhibit at SPI this year but organizers told PV Tech the company cancelled its booth at short notice after filing for chapter 11 bankruptcy in early October 2014.

Despite prolonged efforts, equipment upgrades and process development undertaken by GTAT to meet quality, cost and yield parameters with stakeholders, the consensus was that yield issues had proved the most problematic to overcome and would have required further furnace redesign and development, taking an unspecified time to accomplish. As a result, this prevented Apple from deploying sapphire screens to its new range of iPhones and led to GTAT's bankruptcy.

Wafer business

Daqo expects to be sold out of polysilicon and wafers

China-based polysilicon and wafer producer, Daqo New Energy, has reported record third quarter results, due to strong demand that is expected to continue through the first quarter of 2015. Daqo noted in an earnings call that it was already running its wafer production operations at full-capacity and expected 100% utilisation rates through the first quarter of 2015.

The company is also ramping new polysilicon capacity, noting in the call that it had already secured long-term supply contracts for more than 60% of 2015 capacity and 50% of its 2016 capacity. Management noted that the long-term contracts were only with three customers and that discussions with other potential customers was ongoing, indicating the company soon expects to be fully allocated for at least the next two years.

SAS wafer sales remain strong in October

Taiwan-based solar wafer producer, Sino-American Silicon (SAS), experienced a slight fall in revenue in October, 2014 after rebounding from flagging sales in July and reaching record levels in September.

SAS reported October 2014 sales of NT$2.45 billion (US$80.1 million, compared to US$82.3 million in the previous month. Sino-American Silicon has been buoyed since the beginning of the year from demand for high-quality wafers in Taiwan, China and overseas.

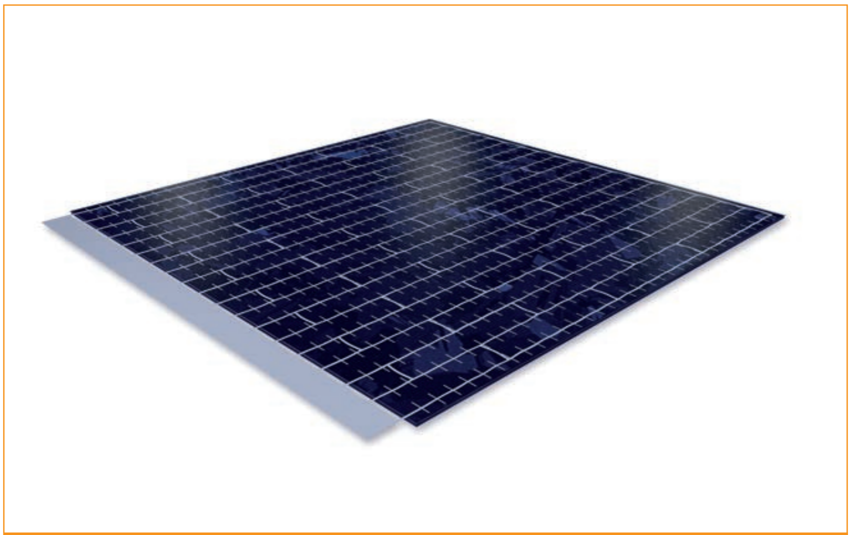
SAS sales dip again in November

Taiwan-based solar wafer producer, Sino-American Silicon (SAS) reported a two month sequential decline in sales. SAS reported sales in November, 2014 of NT$2,383 million (US$76.3 million), down from US$80.1 million in the previous month.

Sales reached a new record in September, 2014. Sales declined 2.7% month-on-month but were still up over 23% form the prior year period.

GCL-Poly confirms sale of solar wafer production assets for US$1.3 billion

GCL-Poly Energy Holdings has confirmed the sale of its wafer production assets for approximately US$1.3 billion in cash. GCL-Poly Energy Holdings had said in early November that it would sell its wafer operations to pay down its high debt situation, created when it went on a massive spending spree to build out the largest capacity of polysilicon production (65,000MT) and wafer production (13GW) in the solar PV industry. The deal with Jiangsu Golden Concord Energy (JGCE) and several other investors was signed on November 29.



Source: GTAT

India's Waree Energies will incorporate GTAT's Merlin technology into its cell lines.

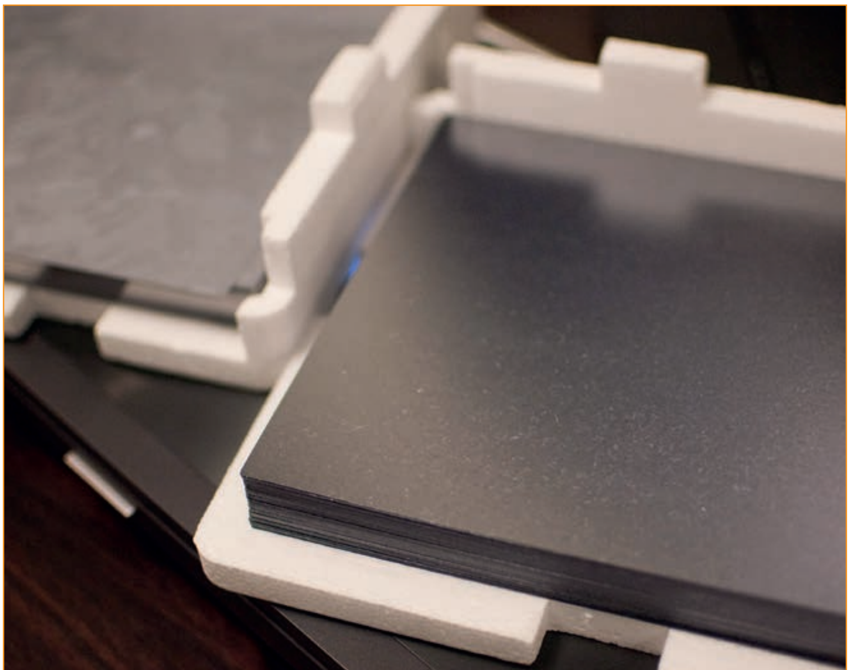
Partnerships

Indian PV module manufacturer collaborates with GTAT on 'Merlin' technology

One of India's largest PV module manufacturer's, Waaree Energies, is to collaborate with GT Advanced Technologies (GTAT) on incorporating its new 'Merlin' technology into its existing production lines.

Waaree said it intended to address "Indian market's diverse needs that range from multi-megawatt solar farms to low cost distributed power implementations", with the use of GTAT's cell metallization and interconnect technology. The company claims this eliminataes the need for tabbing and stringing processes, and leads to an 80% cost reduction in silver paste consumption and an overall 10% cost reduction in system costs.

Waaree said in statement that it "plans to aggressively participate in the Indian EPC/IPP markets and offer industry best-of-class LCOE metrics".



Source: 1366 Technologies

1366 has met a 5MW furnace milestone set a year ago.

Dyesol confirms technology development partnership with UK's SPECIFIC innovation centre

Thin-film OPV firm, Dyesol, has renewed its involvement with Swansea University in Wales and the Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings (SPECIFIC) to develop and commercialize perovskite-based OPV thin-film products.

Dyesol had previously been involved in SPECIFIC with Tata Steel back in 2010, to develop and commercialize liquid-based dye sensitized thin-film coatings and laminates for steel roofing applications. The relationship with Tata Steel goes back to 2007.

REC Silicon expanding polysilicon production and mulling 20,000MT JV in Saudi Arabia

REC Silicon is to expand polysilicon production at its Moses Lake facility and silane production at its Butte facility, while restarting Silane I production.

The company is also undertaking a feasibility study to establish a 20,000MT joint venture polysilicon plant in Saudi Arabia with IDEA Polysilicon.

Company milestones

1366 Technologies meets 5MW furnace milestone

US-Based 'Direct Wafer' producer, 1366 Technologies has met a key production milestone set a year ago of producing 5MW per year for each furnace that is claimed to be on par with conventional ingot casting furnaces used in producing the ubiquitous multicrystalline wafer.

As a result, the start-up company plans to have three "copy exact" furnaces operational in the first quarter of 2015, said to be the final step before building its previously announced 250MW wafer facility.

However, the company also said that other key metrics have also been reached that are intended to secure the ramp of the new facility.

It said it had eliminated the "low efficiency tail" in multi c-Si wafer production, which is an issue with ingot casting techniques that carry higher than wanted impurities and poor crystalline characteristics at various areas of formed ingots.

Wafers produced from these sections of an ingot have lower efficiency ratings and are often re-melted or sold in lower performing modules and low margins.

Source: AGC Solar

Solar glass prices are in for a rebound following huge oversupply.

JinkoSolar's 'Eagle+' modules verified at 306.9 Watts

Major PV manufacturer JinkoSolar has said that its 60-cell multicrystalline silicon 'Eagle+' series modules have achieved power output of 306.9 Watts.

The company said independent tests were recently conducted by TUV Rheinland's Shanghai Testing Center on a sample of the Eagle+ modules under Standard Testing Conditions (STC).

Trina Solar pushes PERC and IBC technologies to record cell efficiencies

Trina Solar has produced n-type and p-type monocrystalline and p-type multicrystalline solar cells with new record conversion efficiencies. Trina Solar expects the technologies used to become part of its future production roadmap.

The company noted that its N-type PERC (Passivated Emitter Rear Contact) designed monocrystalline solar cell, employing an Interdigitated Back Contact (IBC) structure using an industrially feasible production process achieved a record conversion efficiency of 22.9% - on a 156×156 mm2 n-type Cz wafer.

Solar Glass

IHS: Solar glass prices set to rebound following EU-China dispute

From next year, anti-dumping duties levied on Chinese suppliers could contribute to a rebound in the falling price of solar glass, according to a report from IHS Technology. Prices for solar glass have fallen by 50% in the five years between 2009 and 2014, which IHS analyst Karl Melkonyan said could be attributed to "massive oversupply" in the market.

The drop is expected to continue in the very short term, hitting a low of US$4.60 per square metre during this year, having begun at US$10.40 in 2009.

But IHS claims that, driven in part by so-called anti-dumping duties imposed by the European Union (EU) on Chinese importers, this sub-five dollar price will not remain in place for long. Duties were slapped on to solar glass in May this year after the closure of factories and the loss of profits for solar glass makers in Europe.

Xinyi eyes export boost with Malaysia PV glass fab

Xinyi Solar will invest around US$100 million in a new ultra-clear PV glass factory in Malaysia. The company has confirmed the purchase of land in Malacca, Malaysia for the new facility from a government development agency.

China PV glass manufacturer Almaden establishing plant in Dubai

Chang Zhou Almaden a major PV glass manufacturer in China is establishing a new manufacturing plant in Dubai to produce 400,000 PV glass substrates per annum.

The facility was said to cost approximately US$30 million and located in the Dubai Silicon Oasis campus, a free zone technology park in the United Arab Emirates. The plant was said to become operational in the first quarter of 2015.

Five reasons to choose mono-Si

Strategy and Planning Department, LONGi Silicon Materials Corp., Xi'an, China

ABSTRACT
One question to emerge in recent years is whether monocrystalline silicon (mono-Si) or multicrystalline silicon (mc-Si) will become the dominant mainstream technology in the future PV industry. However, despite all the arguments, the market share of mc-Si seems barely changed, while the market share of mono-Si has not increased significantly. The reasons why mono-Si has not made progress have been extensively mentioned in the literature and will therefore not be covered here; rather, the objective of this paper is to discuss several benefits of mono-Si.

Introduction

The advantages of monocrystalline silicon (mono-Si) will be examined in terms of five aspects:

I. Operating lifetime
II. Conversion efficiency
III. System cost
IV. Electricity generation ability
V. Return on investment

I. Operating lifetime

There is an obvious difference between monocrystalline silicon (mono-Si) and multicrystalline silicon (mc-Si) as regards crystalline structure. Mono-Si has a diamond lattice and an almost complete lattice structure, with all the lattice planes having the same orientation; these attributes make mono-Si more stable than mc-Si. The higher crystalline quality also makes mono-Si more reliable, which has been proved in long-term operation. In addition, mono-Si has a longer operating lifetime than mc-Si.

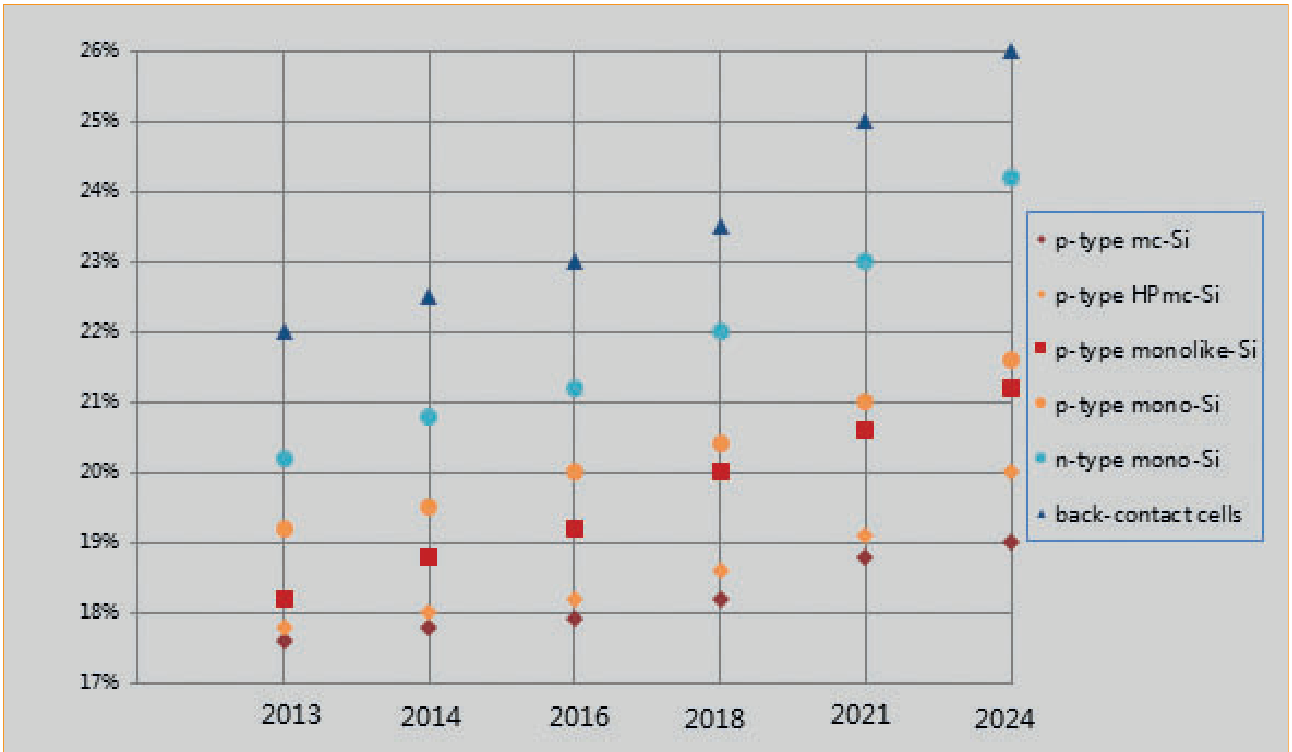
> "Mono-Si has a longer operating lifetime than mc-Si."

At one stage, PV power plants in Europe and test stations in China used only mono-Si modules. Some of these facilities have been operating for more than 25 years: for example, mono-Si modules installed in the 1980s are still in operation today. In contrast, because the development of mc-Si technology has mainly happened only in the past 10 years, more time is necessary to fully test and verify the lifetime of an mc-Si system.

II. Conversion efficiency

A common goal for the PV industry is to seek higher efficiencies because of the low energy density of solar radiation and the high cost of harvesting. Huge amounts of energy from the sun reach the earth every year; however, the solar radiation is very limited in terms of time and area coverage. Taking China as an example, it is estimated that the total solar energy received over its land area of 9.6m square kilometres is equal to the energy produced from 1700bn tonnes of standard coal, which equates to just 177kg of coal per square metre per year. Thus in obtaining the same amount of energy from the sun, the cost of harvesting in relation to the unit area of solar radiation must be calculated.

In the solar energy harvesting



Source: SEMI PV Group Europe [1].

Figure 1. Module conversion efficiency trends for different types of crystalline silicon.

Materials

process, the conventional materials – such as glass, aluminium frames and mounting systems – have been developed over several decades and use mature technology. These materials represent a significant portion of the cost of the solar energy system, and it is difficult to reduce these costs through technological innovation. If calculations are made using an investment cost of US$1.2/W for a PV station in China, then of that amount, US$0.1 is attributable to the solar cell and the remainder to the other, conventional materials; in other words, the solar cell cost is less than 10% of the station cost. Therefore, if the efficiency of the cell doubles, the other costs (amounting to more than 90%) will fall by 50%, meaning that half the amount of glass, aluminium frame and other materials will be used. A 50% reduction in these materials means that, even if the cell processing cost increases by a factor of five, the same system cost can be sustained.

If the cost of the solar cell is not taken into account, and only the cost for the back plate and the stand is considered, then according to calculations of the cost of electricity generation in one square kilometre, solar energy does not make sense if its conversion efficiency is less than 15% (i.e. 15% is the efficiency threshold for the system to make money).

Furthermore, in China and elsewhere in the world, the space available to build PV power plants is very limited. In China, because of the differences in radiation conditions and resource distribution, the main PV stations in the east are distributed systems, whereas in the west they are mainly ground-based stations. There are strict requirements for distributed systems concerning the height of the building, the available roof area, the type of roofing material, the loading capacity of the roof and the lifetime of the roof; as a consequence, the effective rooftop area available for solar is becoming a scarce resource. The desert in the east is even more limited. On a similar note, opportunities for high-quality, ground-based solar plants in the west are gradually decreasing too; although there is a large area of desert and wasteland in the west, after considerations such as water and transformer stations are taken into account, the availability of desert sites for PV power plants is severely limited.

This all means that from the point of view of technical progress, it is a basic requirement for the PV industry to use the limited solar energy and space resources to generate more electricity. Higher conversion efficiencies are the way to go for the development of the PV industry.

Better conversion efficiencies and still plenty of room for improvement

Efficiency improvement is at the core of the development of the PV industry. Right now, mono-Si predominates over mc-Si in terms of conversion efficiency. The conversion efficiencies of n-type mono-Si – such as the heterojunction with intrinsic thin layer (HIT) solar cell from Panasonic and the interdigitated back-contact (IBC) solar cell from SunPower – on a mass-production scale can be close to 25%. The conversion efficiencies of p-type mono-Si cells – such as those offered by LGE and JA Solar – can reach 20% on a mass-production scale. In contrast, it is very difficult for mc-Si solar cells to achieve an efficiency of 19%.

Fig. 1 illustrates graphically the technology roadmap for the PV industry published by SEMI PV Group Europe [1]: the efficiency trends for the different types of crystalline silicon cells are shown. By 2024 the stable efficiency of p-type mc-Si solar cells is predicted to reach only 19%. In comparison, the efficiency of n-type mono-Si cells is expected to be 24.2% and the efficiency of p-type mono-Si cells will probably be 21.6%. As can be seen, there will be differences of 2.5–5.2% abs. in conversion efficiencies between mono-Si and mc-Si on a mass-production scale.

In recent years the passivated-emitter, rear-contact (PERC) cell technology has risen to prominence as a means of improving solar cell efficiency. All the big players in the PV market are currently speeding up the introduction of PERC technology: according to reports, Taiwanese Sunrise has introduced five PERC production lines for cells with a conversion efficiency of 20.7%, and Hanwha Q CELLS has introduced two production lines for cells with a conversion efficiency of 20.2%. Some mc-Si solar cell companies can demonstrate a conversion efficiency of 18.4–18.5% after introducing PERC technology in their cell designs.

From the status of its application by companies in China and overseas, PERC technology shows a better premium advantage and scope for development with the use of mono-Si solar cells. The technology yields a 1% boost in conversion efficiency for mono-Si solar cells, against only 0.5% for their mc-Si counterparts.

"PERC technology shows a better premium advantage and scope for development with the use of mono-Si solar cells."

III. System cost

For a long time, the Chinese market has paid too much attention to system cost, resulting in tough competition within the industry over cost and price. But over time, PV power plant investors have become more rational, while policy guidelines have sought to institute new requirements for a

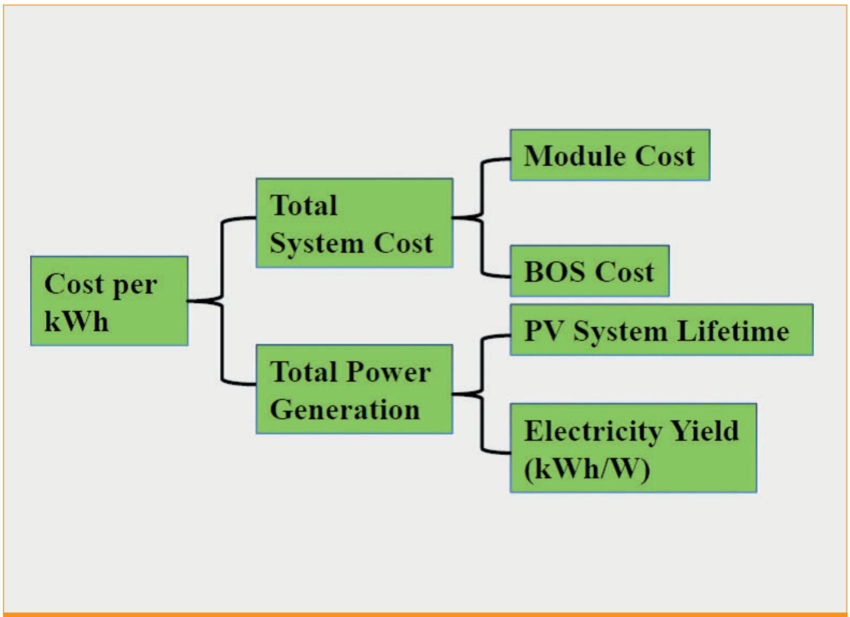


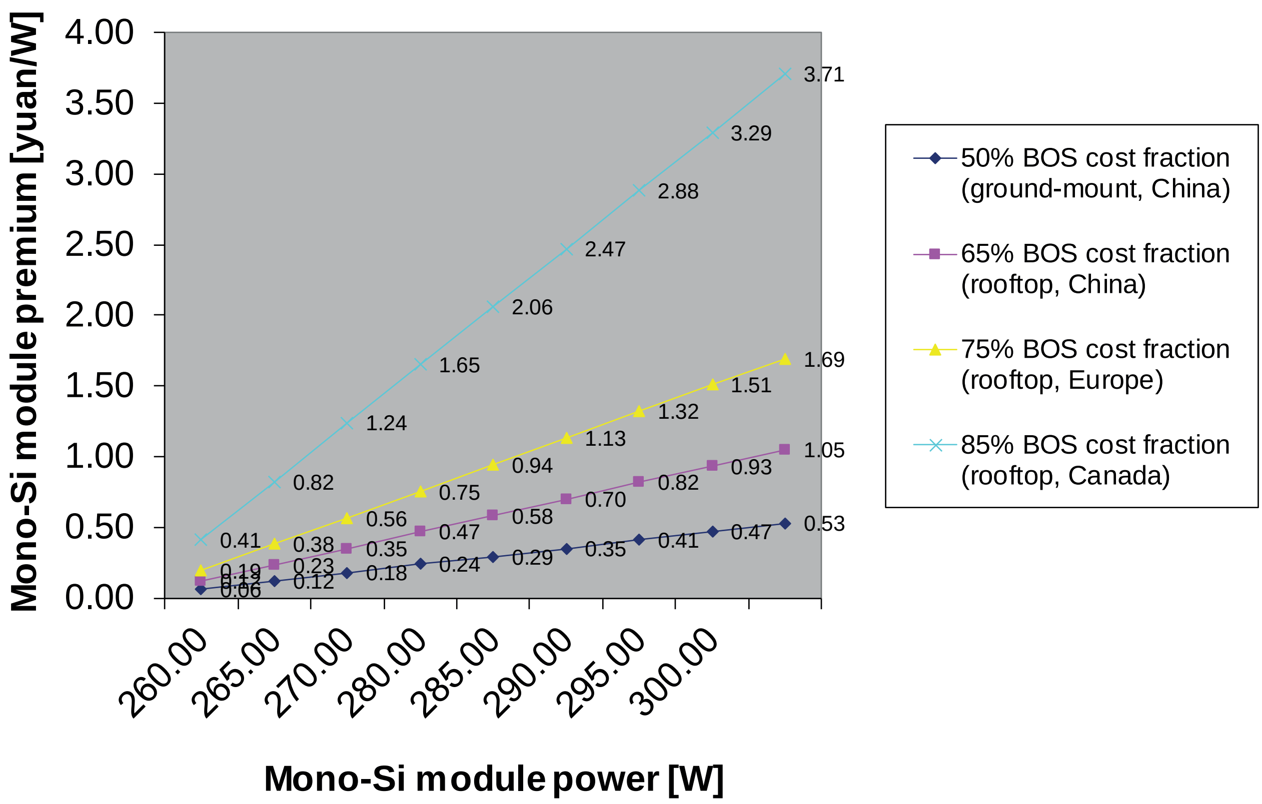
Figure 2. Schematic diagram for the key factors contributing to kWh cost.

healthy and orderly development of the PV industry. As a result, the market has gradually turned its cost focus from per watt to per kilowatt-hour (kWh), in order to benefit electricity generation the most.

The kWh cost is the total unit cost for the electricity injected into the grid. This cost mainly depends on two factors: the station system investment cost and the electricity generated. The system cost consists of module cost and the balance-of-system (BOS) cost, as shown in Fig. 2.

A system cost analysis for a station investment with mono-Si and mc-Si modules will be presented in this section. The current mainstream products are 265W mono-Si modules, which cost 4.3 yuan/watt, and 255W mc-Si modules, which cost 4 yuan/watt; the price difference for the modules is 0.3 yuan/watt.

On the BOS cost side (all other costs apart from the module and which include other equipment, installation labour, construction, and land cost), for an equivalent area the mono-Si modules have a higher power than mc-Si modules, and can thus generate more electricity. Public research and practice show that, for an electrical station with the same power capacity, the mono-Si system can save more BOS cost; and the higher the fraction of the BOS, the better the premium advantage for the mono-Si system. In a Chinese rooftop distributed system, the costs are the same for mono-Si and mc-Si systems. On the other hand, for Japan and Germany, where the BOS cost is higher, the system cost



Source: IHS Solar Solutions statistical data for system costs in various countries.

Figure 3. Cost premium offered by mono-Si for various system types and locations.

Ground-based station in Ningxia [yuan/W]				Rooftop station in Zhejiang [yuan/W}			
Project	Mono-Si	Mc-Si	Difference	Project	Mono-Si	Mc-Si	Difference
Module	4.40	4.10	0.30	Module	4.30	4.00	0.30
BOS	3.40	3.50	–0.10	BOS	2.90	3.10	–0.20
Total	7.80	7.60	0.2	Total	7.20	7.10	0.1

Table 1. Differences in system cost for PV stations in Ningxia and Zhejiang. (Note: mc-Si module = 250W; mono-Si module = 265W.)

for mono-Si is already lower than for mc-Si.

In Fig. 3 the premium of the mono-Si module has been calculated for different power levels (260–300W) with a baseline of 255W and for different BOS fractions (corresponding to different locations and station types). The assumptions for this calculation were:

- A standard power of 255W for the mc-Si module.
- A base module price of 4 yuan/W (tax included).
- No difference in electricity generation between the mono-Si and mc-Si modules.

Taking a ground-based PV station in Ningxia and a rooftop PV unit in Zhejiang as examples, Table 1 lists the differences in system costs. It is easy to see that mono-Si clearly has premium advantages over the mc-Si system in the distributed plant stations and in the region with a high BOS cost fraction.

IV. Electricity generation ability

For the analysis in section III it is assumed that there is no electricity generation difference for the mono-Si and mc-Si modules with the same power. However, because of the variations in crystal structures, mono-Si can generate more electricity. The main differences stem from the following:

1. Mono-Si demonstrates a better temperature effect

Operating temperature is an important parameter for a silicon PV module, impacting both energy conversion efficiency and electricity generation. Mainly owing to the negative temperature coefficient of mono-Si, the photoelectrical conversion efficiency decreases with a rise in the temperature of the solar cell. Every 1°C increase in operating temperature will cause a 0.4–0.5% reduction in module power, and the module will generate less electricity. In theory, the operating temperature of a mono-Si module will be lower than that of an mc-Si module, because of the mono-Si's simple crystalline structure, higher purity, lower inner resistance and higher conversion efficiency. Under the same conditions, a mono-Si module will generate more electricity than its mc-Si counterpart having the same power level.

	Spectral-radiation distribution fraction		
	Standard	AM1.5	Cloudy
Mono-Si response	90.06%	90.44%	89.54%
Mc-Si response	84.1%	84.76%	81.86%
Difference	5.96%	5.68%	7.68%

Table 2. Spectral responses of mono-Si and mc-Si under different lighting conditions.

2. Mono-Si modules degrade more slowly

In general, the degradation of PV modules includes the initial degradation and the long-term degradation. A module will experience a sharp degradation in the first month and then stabilize gradually after reaching a threshold value. Long-term light-soaking tests show that the module efficiency will experience a slight gradual recovery after the long-term radiation exposure. With the same initial degradation, the recovery of a mono-Si module is better than that of an mc-Si module.

At the same time, alternating changes in operating temperature will cause heat stress inside a solar module. The module will break at its weakest point when the heat stress is large enough, which will lead to a drop in module power.

Because of the differences in crystalline structure, theoretically there will be a difference in how well the mono-Si and mc-Si modules can withstand heat stress over time and adapt to changes in temperature and humidity. Mono-Si displays an obvious advantage over mc-Si in dealing with heat stress and adapting to variations in temperature and humidity. Station data for 2012–2013 from the same location in Zhongwei, Ningxia Province, demonstrate that the degradation of mono-Si is 0.34% less than that of mc-Si.

3. Mono-Si modules show better low-light response

To compare the different technologies, mono-Si and mc-Si distributed electrical stations were constructed at Longsheng Silicon Tech Corporation, Qingdao; apart from the type of silicon, all other conditions were the same. One-month operating data show that the mono-Si module can generate 6% more electricity than the mc-Si module with the same power rating. The better the illumination conditions, the greater the advantage of mono-Si over mc-Si. On a cloudy day, the mono-Si will generate 5% more electricity than the mc-Si; on a sunny day, the difference can be as much as 9%.

In fact, mono-Si shows a better spectral response to light on rainy or cloudy days. In his book, *Solar Cells: Operating principles, technology and system applications* [2], Professor Martin Green of the University of New South Wales reports the results of research on the spectral-response range and the capabilities of mono-Si and mc-Si under different radiation conditions. The results show that the mono-Si module has a better short-wavelength range response, which means that in cloudy conditions mono-Si will yield a better spectral response to light than mc-Si (Table 2).

The differences in electrical generation were analysed using the PV mechanism for mono-Si and mc-Si. It was also proved that mono-Si generates more electricity per watt than mc-Si in practical applications. Besides the Longsheng Silicon Tech Corporation project, studies from the Institute of Solar Energy Systems at Sun Yat-Sen University, the China Power Investment Corporation and other companies have also demonstrated that mono-Si generates more electricity than mc-Si.

- Both mono-Si and mc-Si systems were installed at the Institute of Solar Energy Systems at Sun Yat-Sen University to investigate the electricity generation of different technologies. The results between January and July of 2008 show the mono-Si systems generated 5.7% more electricity than their mc-Si counterparts.
- Operating results from companies such as the China Power Investment Corporation in Qinghai, Inner Mongolia and Ningxia demonstrate that the mono-Si systems generated

4.77 to 6.52% more electricity than the mc-Si systems.

- PV electricity stations in Hohhot, Inner Mongolia, consist of both mono-Si and mc-Si systems. Operating results show the mono-Si-based system generated 6% more electricity than the mc-Si one.
- Data from the two 30MW stations in Zhongwei, Ningxia, also show the mono-Si system generated 6.52% more electricity than the mc-Si system in the first quarter of 2014.

V. Return on investment

Whether from policy guidance or as a result of rational industry development, the market is paying more and more attention to the kWh cost. Against this background, the high-efficiency mono-Si system is a good way to lower the kWh cost and improve the return on investment. Perhaps some investors who choose mc-Si still think that mono-Si modules are more expensive. Some cost calculations will now be made for the rooftop electrical station with the following assumptions:

1. The roof area is 40m^2, with a possibility of installing 16 PV modules. Mono-Si modules of 270W and mc-Si modules of 255W are used. The total installation capacity of the rooftop station is 4320W for the mono-Si system and 4080W for the mc-Si system, which means a higher power for the mono-Si system with the same installation area.
2. Investment cost: the rooftop station is on a small scale, and it is assumed that all the other costs are the same for the mono-Si and mc-Si systems. Considering the current market prices – 4 yuan/watt for the 255W mc-Si module and 4.3 yuan/watt for the 270W mono-Si module – there is a 0.3 yuan price difference per watt between the mono-Si and mc-Si modules. The mono-Si system costs 18,576 yuan and the mc-Si system 16,320 yuan.
3. The effective number of sun hours in one year is 1200, which means 1.2kWh per watt.
4. A resident can receive an income of 1.2 yuan for every kWh generated. Of this, 1.0 yuan is the retail price and 0.2 yuan is derived from local government compensation.

Subject to the above conditions, the mono-Si rooftop station generates 5184kWh per year, whereas the mc-Si system generates 4896kWh per year; the mono-Si system therefore generates 288kWh more than the mc-Si system, with a corresponding increase in income of 345.6 yuan. The payback period for the mono-Si system on the extra 2256 yuan investment compared with the mc-Si system is 6.53 years, which is well within the 25-year lifetime of the rooftop system.

Considering the electricity generation advantage per watt for the mono-Si module compared with the mc-Si module, with the same power capacity the mono-Si station generates 5% more than the mc-Si station. The mono-Si station will therefore produce 5443kWh every year, which is 547kWh more than the mc-Si station, with a corresponding income increase of 656.4 yuan. The extra initial investment of 2256 yuan for the mono-Si can then be paid back in only 3.44 years.

> "Even with the higher initial investment cost, the high-efficiency mono-Si module has a lower cost per kWh."

Even with the higher initial investment cost, accounted for within the 25 years' lifetime, the high-efficiency mono-Si module therefore has a lower cost per kWh. Furthermore, as the difference in cost per watt for mono-Si and mc-Si will be smaller in the future, the high-efficiency mono-Si module system will have a greater investment benefit over the mc-Si system.

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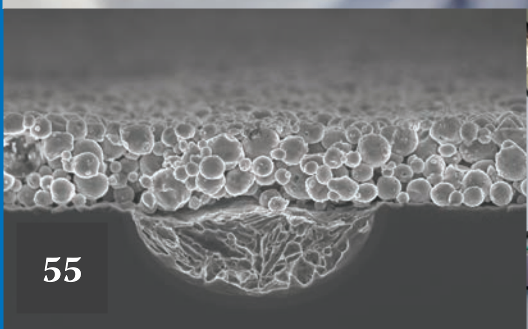
Enquiries

Xi'an LONGi Silicon Materials Corp.
No. 388, Middle Aerospace Road
Chang'an District
Xi'an
China 710100

Tel: (+86) 29-8156 6686-8128
Website: www.longi-silicon.com

Cell Processing



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Bifaciality: One small step for technology, one giant leap for kWh cost reduction

Radovan Kopecek[1], Yannick Veschetti[2], Eric Gerritsen[2], Andreas Schneider[1], Corrado Comparotto[1], Valentin D. Mihailetchi[1], Jan Lossen[1] & Joris Libal[1]

[1]ISC Konstanz, Konstanz, Germany; [2]CEA-INES, Le Bourget du Lac, France

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Simplifying the fabrication of n-PERT solar cells: Recent progress at ISFH

Bianca Lim[1], Fabian Kiefer[1], Nadine Wehmeier[1], Till Brendemühl[1], Yevgeniya Larionova[1], Frank Heinemeyer[1], Jan Krügener[2], Robby Peibst[1] & Thorsten Dullweber[1]

[1]Institute for Solar Energy Research Hamelin (ISFH), Emmerthal; [2]Institute of Electronic Materials and Devices, Leibniz University of Hanover, Germany

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R&D of mass-producible PERC cells with average conversion efficiency over 20%

Wei Shan[1,2], Xiulin Jiang[1], Haibin Yu[1] and Yong Liu[1]

[1]Cell R&D Center, JA Solar Holdings Co. Ltd, Yangzhou, China; [2]JA Solar USA, San Jose, California, USA

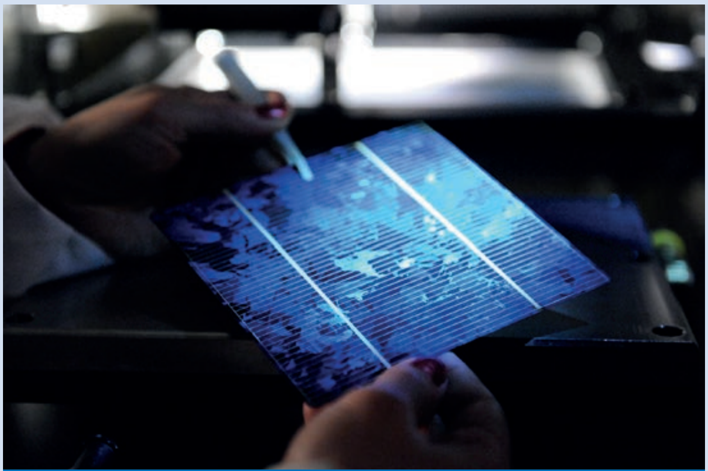
News

PV consumption of silver to continue growing, says Silver Institute

The Silver Institute, a trade association for leading silver producers, expects overall industrial demand for the metal to increase by 27% through to 2018, with demand from the PV industry increasing around 24% over that periiod.

The Silver Institute said that the silver demand in 2013 from the PV industry reached 88 million ounces and should reach annual demand of 109 million ounces through to 2018, despite decreasing unit consumption.

The increase in global demand is expected to be led by key markets such as China, Japan, the US and Europe, with emerging markets such as India and Latin America increasingly accounting for demand the in the future. Demand is expected to also increase in the Middle East and North Africa within the timeframe.



Source: DuPont

Demand for silver in PV cells will go up 24% by 2018.

According to the Silver Institute, silver industrial demand in Europe fell to 91Moz in 2013, compared to 105Moz in 2004, while Chinese industrial consumption had increased to 117Moz, up from 56Moz in 2004. China was said to have generated about 54% of global silver PV demand in 2012.

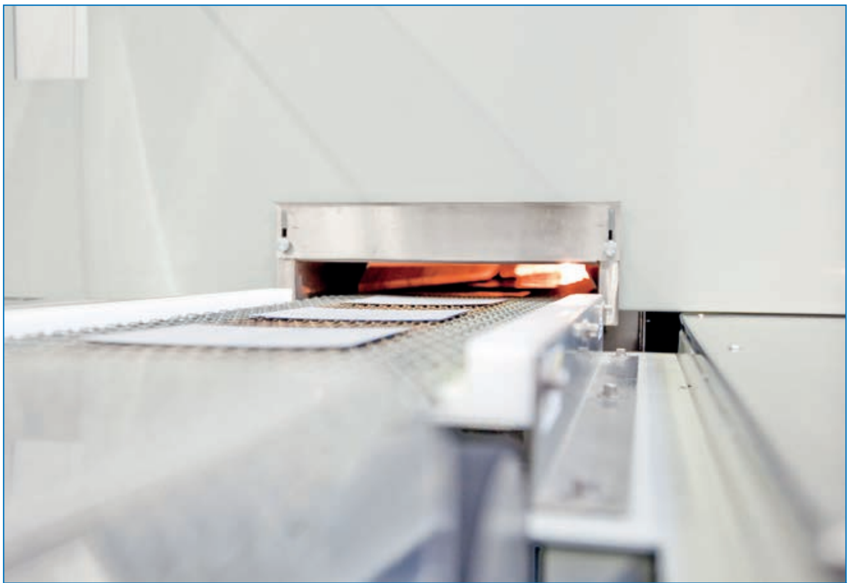
However, the trading price for silver has fallen rapidly since 2011, when it reached over US$46.06 per ounce to around US$17 per ounce in the second half of 2014. According to the Silver Institute, 1MW PV modules on average, consumes approximately 90kg of silver paste material.

Mergers and joint ventures

JA Solar and DuPont seal R&D pact

JA Solar, the fastest growing PV manufacturer in 2014, has signed a strategic cooperation agreement with PV materials and technology specialist DuPont.

The companies held a signing ceremony at the DuPont China R&D Center in Shanghai on 9 December 2014 that will see the pair continue to work together on solar cell technology and advanced materials for increased cell efficiencies and product durability.



Source: Hanwha Q CELLS

The merger of Hanwah's SolarOne and Q CELLS subsidiaries will create a cell manufacturing giant

BTU International acquisition was planned ahead of expected capex upturn

The acquisition by Amtech Systems of BTU International was pre-planned to be completed and the company assimilated into Amtech ahead of the next capacity expansion phase by major PV manufacturers, according to Paul van der Wansem, chairman and CEO of BTU International.

The Amtech acquisition is being touted as a way for BTU to gain better exposure to the PV market than it had achieved in the past with the opportunity to be better represented in markets such as China and Asia Pacific as well as the US, which is having a recent renaissance in c-Si manufacturing plans, especially for N-type monocrystalline solar cell technology.

Hanwha to create 3GW cell giant with Q CELLS and SolarOne merger

The merger of Hanwha SolarOne and Hanwha Q CELLS is set to proceed in a deal estimated to cost Hanwha SolarOne around US$1.2 billion in an all-stock transaction.

The merger of Hanwha Q CELLS and Hanwha SolarOne had been expected for some time, since Hanwha Chemical and Hanwha Group, both interrelated Korean companies, separately acquired the then bankrupt Q-Cells, and struggling Chinese module manufacturer, Solarfun.

Hanwha claimed the combined entity would become the world's largest manufacturer of solar cells with a capacity of 3.28GW. According to NPD Solarbuzz data before the IHS acquisition, Yingli Green had become the largest solar cell producer in 2013 for the first time with production in excess of 2GW.

Source: Neo Solar Power.

Neo Solar Power has seen the beginnings of a recover in its cell sales.

Capacity expansions

Canadian Solar adding solar cell capacity after record third quarter results

Canadian Solar has confirmed it will expand its PV module capacity by 500MW, and also announced plans to add 400MW of high-efficiency solar cell capacity, while upgrading existing production lines to higher efficiencies.

This is after the major PV energy provider, reported record quarterly results for the third quarter of 2014, while guiding higher shipments and revenue for the fourth quarter.

Canadian Solar noted that due to strong demand from a number of key markets it would expand production.

The company confirmed reports that it would expand PV module production by 500MW at its Changshu and Luoyang plants in China, which are expected to be complete in the second quarter of 2015. Capacity expansions were to come online throughout the first two quarters of next year.

Total nameplate PV module capacity would therefore stand at 3.5GW by the end of the second quarter of 2015.

However, the company also announced a major expansion of solar cell capacity with several high-efficiency developments. Firstly, Canadian Solar said it was installing its first 80MW cell line dedicated to high efficiency multicrystalline solar cell production at its plant in Funing, Jiangsu Province, which was said to be progressing well and that it expected to further expand this high efficiency cell facility to 400MW by the second quarter of 2015.

This would increase in-house nameplate solar cell capacity to 1.9GW.

Vikram Solar mulls module capacity expansion and cell production partnership in India

India-based PV module manufacturer, Vikram Solar, has said it is evaluating its next module capacity expansion plans as well as a new joint venture to establish solar cell production with a major existing producer.

Vikram Solar has an existing PV module nameplate capacity of approximately 150MW, which it said it was considering expanding by a further 200MW to reach a cumulative capacity of 350MW by the second quarter of 2015.

In a more bold move, Vikram Solar said that a second phase expansion could result in cumulative module capacity reaching 600MW (250MW incremental) by the fourth quarter of 2015.

Changing fortunes for Taiwanese cell manufacturers

Motech sees sales rise

Having seen a rebound in sales in September, Taiwan-based PV producer, Motech Industries reported sales flat in October, 2014. Motech reported sales of NT$1,550 million (US$50.65 million), compared to NT$1,553 million (US$51.08 million) in the month of September. Motech's sales recovery would seem to have peaked quickly after being one of the worst hit by the US anti-dumping decision, which saw sales declining since April and only rebounded in September.

But the company reported relatively strong sales in November, seeing a recovery to levels before sales declined earlier in the year due to the US anti-dumping case.

Motech reported November 2014 sales of NT$1,805 million (US$57.8 million), compared to US$50.65 million in the previous month and US$51.08 million in the month of September. Sales had been on a strong downward trend since April.

Rebound for Gintech cell sales

Taiwan-based solar cell producer, Gintech Energy reported October 2014 monthly sales of NT$904 million (US$29.55 million), down 14.2% from the previous month.

Gintech Energy then reported a major turnaround in monthly sales for November, having seen a slide since June, due to the US anti-dumping case.

Gintech reported sales in November 2014 of NT$1,520 million (US$48.7 million), up 68.3% from the previous month when sales were US$29.55 million and down 14.2% from the month of September. The increase in sales is believed to be due to strong demand in Asia, notably China and Japan, offsetting a significant slowdown in demand from Chinese customers due to the US anti-dumping case.

Slow recovery for Neo Solar Power sales

The largest merchant solar cell producer, Neo Solar Power Corporation (NSP), reported a net loss in the third quarter of 2014, due to the imposition of US anti-dumping duties on Taiwanese-made solar cells.

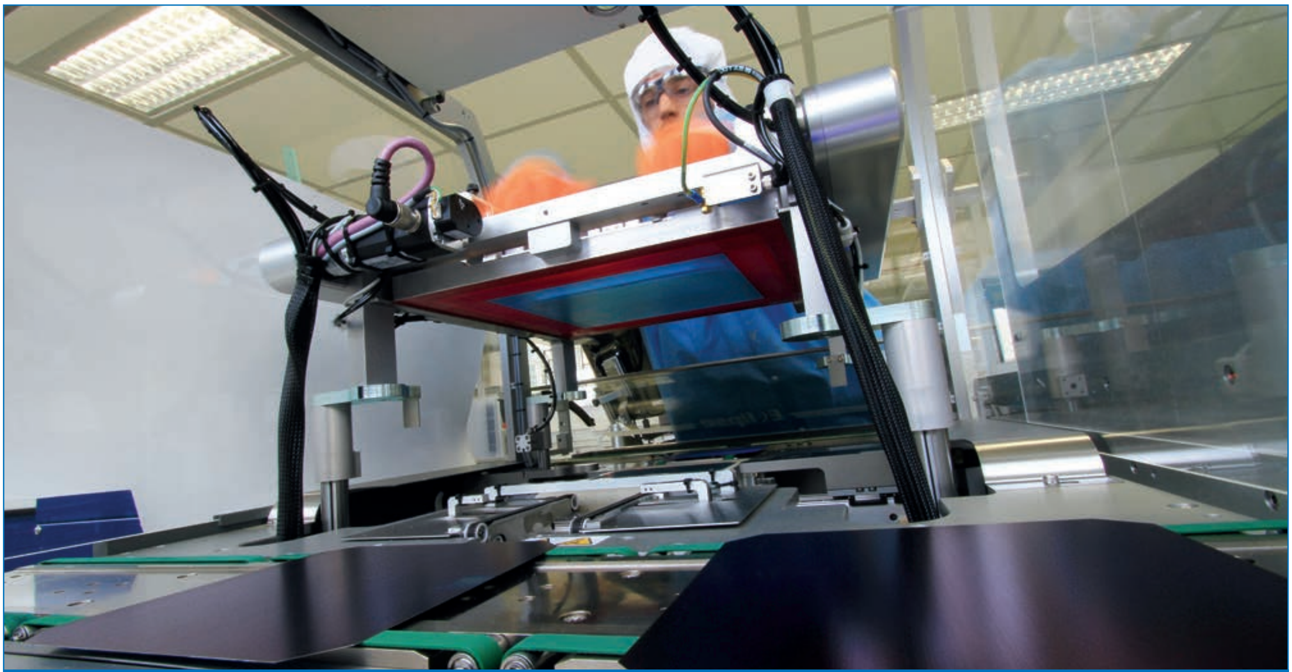
NSP reported third quarter revenue of NT$5,887 million (US$192.6 million) and revenue for the first nine months of 2014 of NT$20,551 million (US$672.6 million). Operating loss was NT$118 million (US$3.8 million) in the third quarter and a net loss of NT$153 million (US$5 million).

In November the company saw a slow recovery in monthly revenue after peaking with record revenue in May 2014. NSP reported November revenue of NT$2.096 billion (US$67.4 million), compared to October revenue of NT$2.057 billion (US$67.3 million), up from US$64.7 million in September.

R&D hits manufacturing floor

Yingli Green includes MWT and ion implant to 'PANDA' technology roadmap

Yingli Green Energy updated the financial community as to its long-term technology roadmap during its fifth annual investor day event during Solar Power International 2014, held in Las Vegas in October.


Source: Meyer Burger.

Meyer Burger has opened its HJT cell pilot line in Switzerland.

Brian Grenko, vice president, technology at Yingli Green Energy Americas discussed both multicrystalline (multi c-Si) and monocrystalline (mono c-Si) technology roadmaps that remain on-track to meet commercial production efficiency targets in 2020 of 19% and 23% respectively.

Unsurprisingly, Grenko highlighted that higher quality wafers were a key part of the overall cell efficiency drive within Yingli Green's multi c-Si technology roadmap.

However, the benefits also transcended lower manufacturing costs, a key driver of the company for many years. As such the focus hasn't changed much, with a continued focus on the optimisation of its DSS furnace casting process that it designed to continuously lower the defect densities.

Grenko noted that changes in the ingot crucible used by the company had led to increased ingot yield, lower defect density as well as lower costs. Modifications to the crucible geometry, further cycle time reductions and lower electricity costs were key contributors.

Meyer Burger opens heterojunction solar cell pilot line with CSEM

Major PV equipment supplier, Meyer Burger has officially opened its heterojunction (HJ) solar cell pilot production line with CSEM at subsidiary, Meyer Burger Research AG in Hauterive, Neuchâtel, Switzerland.

The pilot line is part of the wide-ranging Swiss-Inno HJ technology project that also involves the Swiss Federal Office of Energy and the Canton of Neuchâtel and is a key part of Meyer Burger's attempts to attract PV manufacturers to adopt its co-developed HJ technology into volume production.

The technology partners noted that the pilot line has a production capacity of 600 kilowatts, from which HJ manufactured cells are built into modules and tested in both the laboratory and in the field.

The target upon further process optimisation is to reach a PV module efficiency of 21% but with a production cost below 0.6CHF/Wp (US$0.62/Wp). HJT cells are said to achieve an efficiency of more than 22% in lab conditions.

JA Solar pushes 60-cell multi-Si module to 280W

Major China-based PV manufacturer, JA Solar, has had TÜV Rheinland verify that its PERC cell technology modules have a record-high >17.2% conversion efficiency, producing a standard 60-cell module with a performance figure above 280W.

The figures were recently confirmed and certified by TUV Rheinland at its Shanghai Testing Centre, according to JA Solar.

Panasonic HIT modules pass TÜV Rheinland's salt mist corrosion tests

Panasonic has passed TÜV Rheinland's salt mist corrosion testing for its latest photovoltaic (PV) module type, the manufacturer announced in October.

The tests were applied to Panasonic's HIT modules, VBHN245SJ25 and VBHN240SJ25. The upgraded modules were launched at the beginning of 2014, with the company citing a conversion efficiency of 19.4%, aimed at providing an improvement from the company's previously available modules in overall operational performance, notably for residential rooftop markets. The solar cells in a HIT module are made of a mono thin crystalline silicon wafer surrounded by ultra-thin layers of amorphous silicon.

PECVD tool orders

Orbotech gets follow on US$15 million deal

Semiconductor and solar equipment supplier, Orbotech, has received a repeat order for its 'Aurora' PECVD tools worth around US$15 million.

The follow on order with its subsidiary, Orbotech LT Solar (OLT Solar), is larger than the initial US$10 million order in December 2013 from an unidentified tier-one PV module manufacturer.

Israel-based Orbotech noted that the multiple tool order would start shipping during the first half of 2015.

Amtech to ship PECVD tools for Mission Solar's planned capacity expansion

PV equipment specialist, Amtech Systems, has secured a follow-on order with US-based PV manufacturer, Mission Solar, in a multi-million dollar deal said to be in the low teens.

The deal includes equipment from its Tempress Systems subsidiary and includes PECVD tools. Mission Solar is currently planning to expand production of its n-type monocystalline cell and module plant from 100MW to 200MW in 2015.

Product Reviews

VITRONIC

VITRONIC's solar cell inspection systems offers 4,000wph throughput

Product Outline: VITRONIC's latest generation of VINSPECsolar inspection system uses a high pixel resolution of 20µm and a robust sensor unit with the camera system to deliver the throughput of up to 4,000 wafers per hour. The system is claimed to provide adapted and differentiated classification options to master the inspection and classification tasks required for latest high-efficiency cells and modern metallization processes with very thin fingers

Problem: Manual visual inspections are unable to compete with the latest machine vision technology from either a qualitative or a cost perspective. However, PV manufacturers can only hold their ground on the market by offering high-quality, clearly classified products. Optical quality inspection is required during PV production especially on more advanced cell designs such as PERC to obtain and maintain high yields.

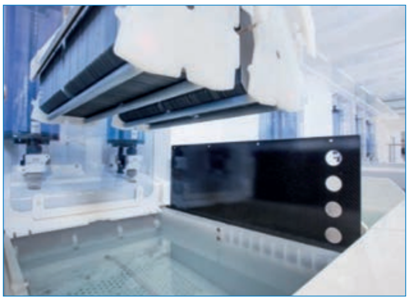
Solution: In cell testers and sorters, the high-performance defect detection combined with reliable and differentiated colour classification ensures optimum results. Integrated in standard production equipment, the physical performance, robustness and reliability of the system is claimed to give an investment return within only a few months.

Applications: Inspects for micro cracks, which are relevant for efficiency and cell survival. The system also measures granularity, the grain structure of multicrystalline wafers and detects severe saw marks, holes and chippings.

Platform: VINSPECsolar is suited to solar cells with edge lengths of up to 8" and for a range of different formats, e.g. pseudo square and full square as well as various crystalline structures.

Availability: Currently available.

RENA



IPA-free wafer texturing process from RENA offers lower cost solution

Product Outline: RENA, in collaboration with imec, has developed a novel isopropyl-alcohol (IPA)-free process for the texturing of Cz-Si wafers, dubbed 'monoTEX F.' RENA's next-generation texturing additive is claimed to support conversion efficiencies well above 21%.

Problem: Wafer texturing chemicals are typically based on the chemistries of the industrial additive, IPA, which evaporates at higher temperatures, reducing the chemical concentration stability and performance as its process temperature and boiling point are in the same temperature range. IPA-based texturing can therefore be more expensive as bath lifetimes can be lower than alternative solutions.

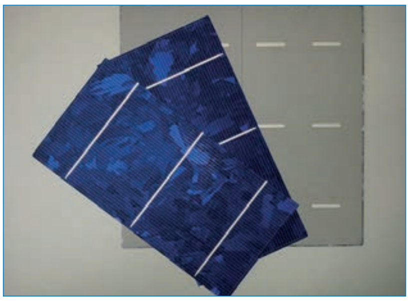
Solution: monoTEX F is a moderating and wetting agent that is said to behave in almost a "linear" fashion towards changes in process temperature and alkali concentration. This enables it to operate at temperatures far below its boiling point, negating evaporation and providing a stable concentration of ratios in the etching mixture during the texturing process step. As a result, monoTEX F simplifies the texturing and widens the texturing process window all at once, while increasing the texturing bath lifetime helps lower overall process costs. According to imec, when applying this novel monoTEX F-based texturing in its silicon PV pilot line to process large area (156x156 mm2) PERC-type solar cells, they achieved excellent conversion efficiencies well above 21%.

Applications: Texturing of Cz-Si wafers.

Platform: monoTEX F is compatible with a number of RENA platforms that range from lab, pilot line up to high volume designs for GW PV-companies for cost optimized and space saving operation.

Availability: Currently available.

InnoLas



InnoLas provides volume production cell grooving and cutting tool

Product Outline: InnoLas Solutions has developed an automated laser machine with an integrated with soft wafer breaking process to produce half cells or quarter cells for later module assembly.

Problem: The device-inherent resistivity together with the high photo-induced current of solar cells within one string is causing significant electrical losses when cell-to-cell interconnection takes place during the stringing process. This represents one of the main contributors to electrical performance and has therefore a high impact on later module efficiency.

Solution: When using half or quarter cells instead of full cells, the impact of the cell resistivity in one string can be lowered due to the reduction of the photo-induced current per unit cell. As a result of a German research institute's investigation, the output power of half-cell modules increases up to 10-15W. A six-month real-world outdoor measurement test in Germany using half-cell modules confirmed a + 3% higher average module power yield in comparison to standard modules and represents a strong argument for using cell cutting to reduce C2M losses, InnoLas said. The company offers an integrated solution based on its new ILM-2 laser machine and handling platform for an advanced, precise and high-aspect ratio laser grooving process together with a soft breaking method.

Applications: Wafer/cell grooving and cutting for ½ and ¼ sizes.

Platform: The ILM-2 laser machine and handling platform comes with a high throughput of 2850 cells/hour. The ILM-2 is a modular machine concept that can be used as a stand-alone or in-line system, with the option to use different laser sources and different automation concepts.

Availability: Currently available.

Bifaciality: One small step for technology, one giant leap for kWh cost reduction

Radovan Kopecek[1], **Yannick Veschetti**[2], **Eric Gerritsen**[2], **Andreas Schneider**[1], **Corrado Comparotto**[1], **Valentin D. Mihailetchi**[1], **Jan Lossen**[1] & **Joris Libal**[1]

[1]ISC Konstanz, Konstanz, Germany; [2]CEA-INES, Le Bourget du Lac, France

ABSTRACT

The aim of this paper is to dispel the common belief that bifaciality is nonsense as it is not a mature technology, it is expensive and, because in large systems there is limited albedo from the rear side, it only serves the niche market. A complete picture of bifacial cell technologies and module concepts is presented, as well as levelized cost of electricity (LCOE) results for present and future bifacial systems.

Introduction

At a time when high-efficiency solar cell technologies are in any case moving towards bifaciality, and many module producers are changing to glass–glass, as well as the fact that high-power modules are necessary in order to minimize the balance of system (BOS) costs, the authors are very confident that bifaciality will become an extremely important technology in driving down costs per kWh for PV systems. When rooftops are the main market in a particular location (e.g. the Netherlands), bifaciality is, needless to say, not of great interest. However, for flat roofs and ground-mounted installations of large systems (e.g. in desert areas), bifaciality is extremely helpful for driving down the levelized cost of electricity (LCOE) and also for increasing the duration of electricity generation.

> "For flat roofs and ground-mounted installations of large systems bifaciality is extremely helpful for driving down the LCOE."

There are still several technological challenges which are not trivial: for example, how to design and where to place the junction boxes, how to build shadowless and stable mounting systems and, most importantly, how to standardize bifacial measurements and how to simulate the bifacial benefit of individual installations. However, all of these challenges have already been tackled individually for some time by a number of companies and institutes. This article summarizes some of these outcomes, which were presented and discussed at the Second BifiPV Workshop in Chambéry, revealing

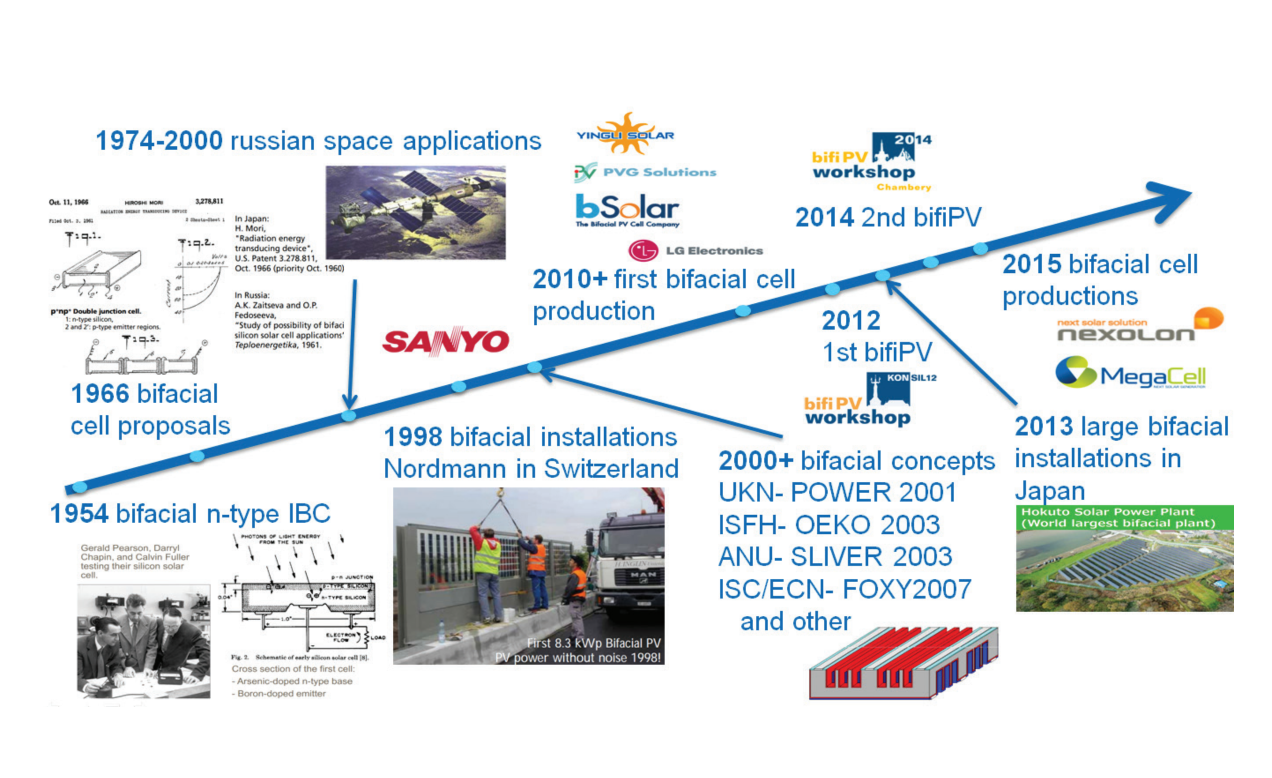
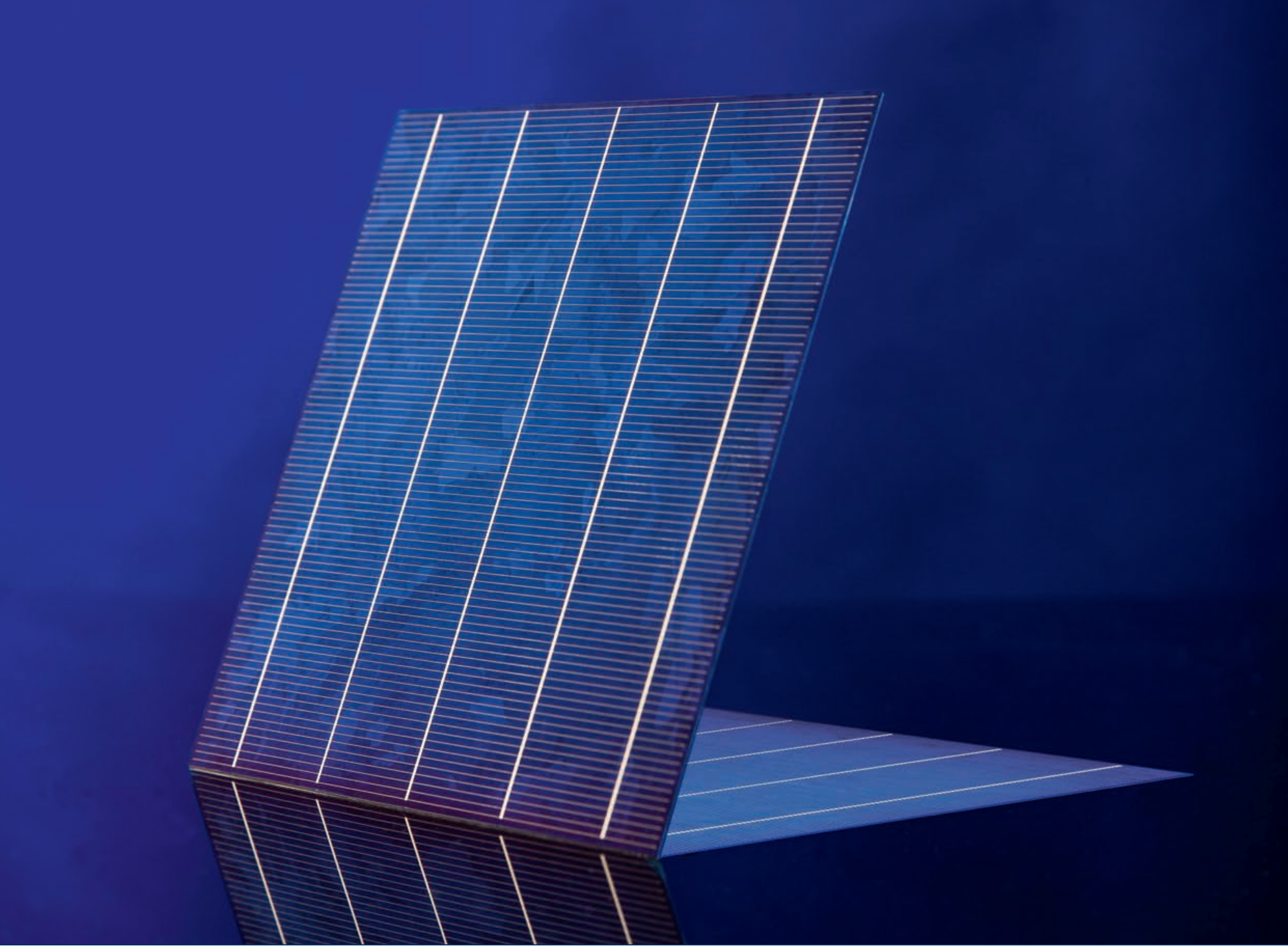


Figure 1. Brief history of bifacial cells, modules and systems.



the big picture of the status of bifacial technology. At that workshop several working groups were established, assigned to work on standards for bifacial measurements, qualification standards for bifacial modules and the development of dedicated simulations of bifacial systems.

Bifacial history and status, and estimations of LCOE

History and status

Bifacial solar cells have a very long history. The concept actually originated at Bell Labs in 1954 with the very first solar cell processed, which was an n-type bifacial interdigitated back contact (IBC) solar cell. The history is depicted in Fig. 1, as presented by Kopecek at the Second bifiPV Workshop [1]. Russian and Spanish groups made proposals in the 1960s on how bifaciality could be used, and bifacial cells have been employed in space applications in Russian satellites since the 1970s. Around 2000 bifacial modules have also been used in terrestrial applications, for example by Nordmann [2] on Swiss highways. However, all the cell and module concepts employed at that time were extremely expensive, so these systems were strictly niche applications, in which costs were not a concern (e.g. space applications), or they were used for demonstrations.

Since 2000, several groups have been picking up the idea of bifaciality again: with the development of, for example, cost-effective n-type solar cells, bifacial technology is being borne in mind in order to benefit from the active rear side. One of the first cost-effective bifacial mc-Si solar cells is described in the Ph.D. thesis of Kränzl [3]. The institutes ECN and ISC Konstanz were partners in the successful EU-funded FoXy project, running from 2006 to 2008 within the Sixth Framework Programme (FP6) [4]. The project dealt with low-cost silicon and cost-effective n-type cell and module processes for mass production.

Today, six years later, the n-type processes are being used in several industrial production lines, under such designations as n-PASHA (ECN) and BiSoN (ISC Konstanz) solar cells. ECN and European OEMs have successfully transferred their n-type technologies to cell and module manufacturers outside Europe (Yingli, Mission Solar Energy), while ISC Konstanz is currently transferring the BiSoN process to MegaCell in Italy. Mission Solar Energy and MegaCell are investing in the installation of additional solar cell capacity because of bifaciality.

Electricity costs with bifaciality

Photovoltaics' share in EU renewable electricity production could be substantially increased if its cost structure were to further improve. The cost of solar electricity can be reduced by increasing efficiency, implementing low-cost manufacturing technologies, and improving reliability and sustainability. A fourth powerful approach to reducing cost is to increase the energy yield, namely the kWh produced per Wp module power. The important metric for analysing cost is the LCOE, which takes into account the costs and the energy produced over the system lifetime.

In southern Germany the current value of LCOE for a state-of-the-art system is around €ct8/kWh. Although most of the cell and module manufacturing has moved to Asia,

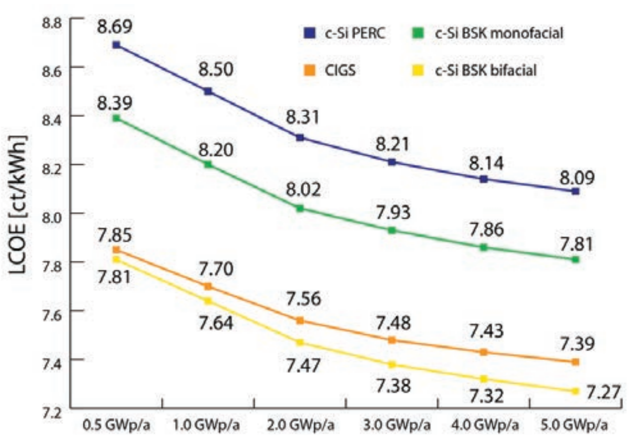


Figure 2. LCOEs of a PV system in southern Germany for different technologies as a function of the scale of production (GW study of FHG IPA/ISE). A range of €ct8.2–8.69/kWh is calculated for the production of standard c-Si technology on a 0.5–1GWp/a scale.

Today (2014)	Solar cells in 2020+	Bifaciality in 2020+
Cz-Si cell Efficiency: >20% Power: 5Wp Costs: €0.3/Wp	**Cz-Si cell** Efficiency: >24% Power: 5.7+Wp Costs: €0.2/Wp	**Bifaciality factor: 0.8** Effective power: up to 450Wp-e*
60-cell module Cell-to-module loss: 3% Power: >290Wp Costs: €0.55/Wp	**60-cell module** Cell-to-module gain: 2% Power: >350Wp Costs: €0.4/Wp	Yearly system power gain: 15–30% (depending on installation) A conventional 0.7GW factory when upgraded to this technology will produce 1GW
System in southern Germany Costs: €1.5/Wp Electricity production costs (running for 25 years): €ct8.5/kWh	**System in southern Germany** Costs: €1.1/Wp (reduction in module and system costs through decrease in area) Electricity production costs (running for 30 years): €ct6/kWh	**System in southern Germany** (running for 40 years/improved reliability with glass–glass): down to €ct3–4/kWh

* Wp-e is the real effective peak power that is generated by a module mounted in a system. For a module with a high BF, Wp-e can be more that 30% higher than the measured front-side power Wp.

Table 1. Cost of ownership (CoO) for cells and modules and the resulting LCOE for current and future monofacial and bifacial technologies. (The bifaciality factor – BF – is the ratio between rear- and front-side efficiency; for identical efficiencies the BF is 1.)

large-scale production is expected to become competitive in Europe. A recent study by Fraunhofer, with other similar studies coming to the same conclusion, predicted that multi-GWp production in Europe based on relatively conventional technology can be cost effective at this state-of-the-art LCOE (see Fig. 2). Moreover, if bifaciality is considered, solar cell production on an even smaller scale can be cost effective. Table 1 shows the results of the calculation of LCOE for today's systems with standard technology and future systems with higher efficiency and increased power output using bifaciality.

The cell and module concepts of many institutes and companies aim for higher cell efficiencies (>24%) and lower overall manufacturing cost (including silicon material and crystallization, a very important cost factor), leading to a reduction in LCOE to €ct6/kWh (monofacial application), and higher yearly output (using a novel bifacial high-efficiency module architecture) plus longer lifetime targeting down to €ct3–4/kWh for most optimal bifacial operations.

Bifacial solar cells

The last few years have seen a steady improvement in cell and module performance. Currently, the standard technology – aluminium back-surface field (BSF) on p-type silicon – represents a very large proportion (>90%) of world production, with efficiencies of over 19% on Cz substrates [5]. This progress is largely due to the development of advanced metallization pastes, which allow the formation of a lightly doped emitter and reduced shadowing over the front side of the cell. Nevertheless, it is expected that the performance will be limited in the near future because of the rear surface (passivation and light confinement issues). Different lines of attack are therefore essential in order to produce cells of higher efficiencies.

For many cell producers, the passivated emitter rear cell (PERC) concept represents a natural continuation of standard technology. Such cells are already in production on a large scale in Asia, with an efficiency of over 20%, not taking into account light-induced degradation (LID). Compared with the reference technology, additional steps are necessary, such as rear-surface cleaning, dielectric layer deposition (Al_2O_3, SiO_2) and laser opening [6].

Alternatives technologies to the PERC concept can also be considered, such as the passivated emitter rear totally diffused (PERT), the a-Si:H/c-Si heterojunction (HJT) and the IBC (Fig. 3). All these three architectures have one thing in common: they can be bifacial. When such cells can benefit from an albedo, the gain in yield can be impressive, as stated by Kreinin [7], who reported that an 18.5% cell mounted over a surface with intermediate albedo can yield a bifacial gain of 20%, corresponding to an equivalent cell efficiency of 22%.

As in the case of PERC, the PERT cell has the advantage of being more compatible with existing production lines; indeed, only a few additional manufacturing tools are required to make the step from standard technology. The PERT cell architecture, depicted in Fig. 3, is made up of two diffused layers, namely p^+ for the emitter and n^+ for the BSF on each surface. Anti-reflection dielectric coatings (SiN) and symmetrical contacting grids are deposited on both sides.

The PERT cell is commonly developed on n-type Cz substrates to avoid the LID effect (absence of the boron–oxygen complex). This technology requires three main additional steps: 1) boron diffusion for the emitter formation (p^+); 2) emitter passivation; and 3) the use of specific screen-printing pastes for contacting the boron emitter. As regards the boron diffusion, a higher thermal budget in the range 900–1050°C is required, depending on the technology. So far, gas diffusion (BBr_3, BCl_3) is the approach most commonly adopted, and is currently used in production probably because it is a more mature process [8,9]. Ion implantation is an alternative, as excellent efficiencies with simple process flows have been reported [10,11]. The use of solid sources is another option via the use of PECVD doped oxides or spin-on dopants [12,13]: for example, the technology of PVG Solutions (30MW

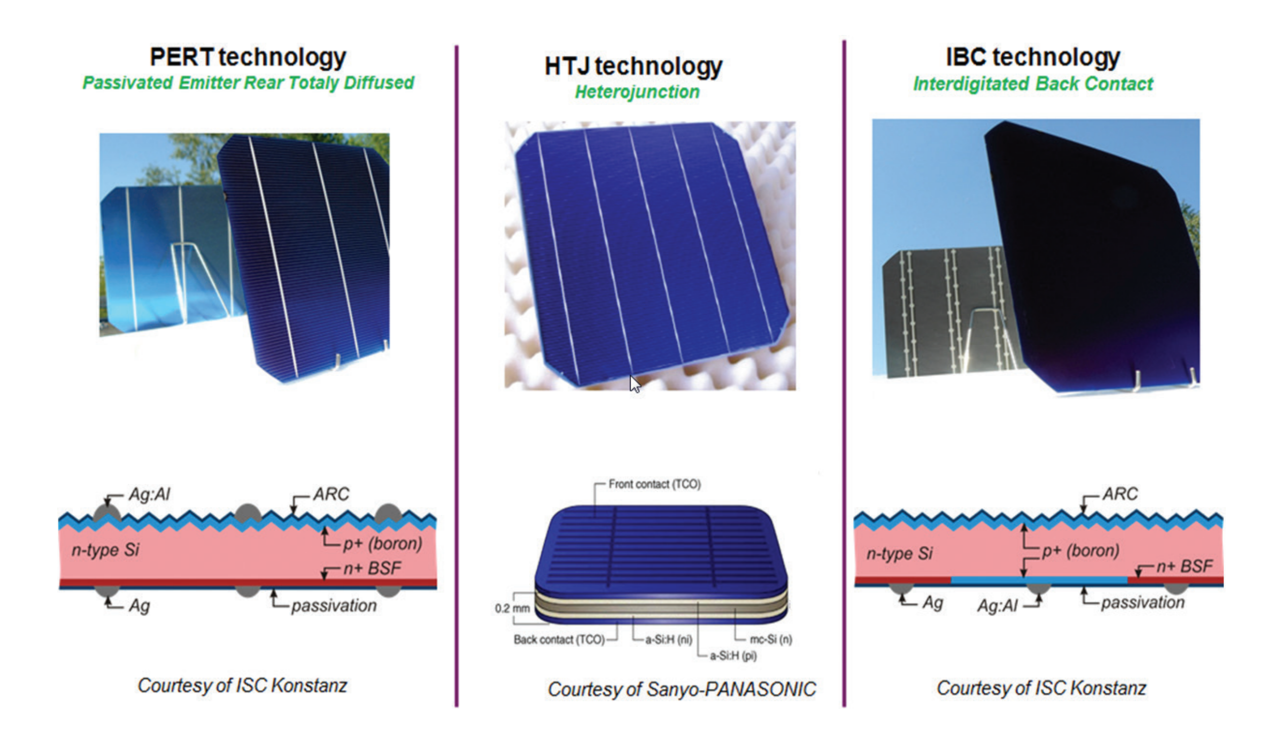


Figure 3. Most prominent n-type technologies with bifacial characteristics.

production line of bifacial cells) is based on the use of spin-on dopants [14]. The emitter passivation can be performed by silicon oxide growth (dry or wet), by Al_2O_3 layer deposition (PECVD, ALD) or by alternatives such as the nitric acid oxidation of Si (NAOS) concept (chemically grown oxide) [15,16]. Dedicated metallic pastes (Ag/Al) are finally deposited by screen printing to contact the boron emitter. As a consequence, quite different process flows are possible for the fabrication of PERT cells (Fig. 4). The compromise between cell efficiency and process simplification remains the principal guideline with regard to industrialization.

In 2009 ECN was one of the leaders in this technology, presenting an efficiency of 18.5% with its PASHA technology. Since then, many players (academics, equipment suppliers or cell producers), including ECN, have reported efficiencies of between 20% and 21.3% (see Fig. 5).

Experts in the field are confident that – for the diffused technologies – efficiencies over 21% should be achieved in 2015. The main factor that limits efficiency is the high recombination activity at the metal/p^+–Si emitter interface, which corresponds to 40% of the total cell J_0 [17]. Most players report a large gap between the implied V_{oc} value measured on the cell before metallization and the final V_{oc} value. Even if the Ag/Al pastes were regularly improved in order to print narrower fingers, efficiencies nudging 22% will be difficult to achieve if the issue above is not resolved. Alternatives such as copper plating and passivated contact concepts are now under investigation to determine their feasibility in competing in the near future with alternative technologies like HJT and IBC. Nevertheless, since the V_{oc} value remains limited, the PERT cell is a lot less sensitive to the substrate quality.

There are currently four producers of bifacial PERT cells – Yingli (PANDA), LG (MonoX NeOn), PVG Solutions (EarthON) and Neo Solar Power – and more producers of PERT cells are expected in 2015.

A possible evolution of the PERT cell could be in the direction of IBC; this cell structure is well known to have a very high efficiency potential because of the absence of metallization on the front side. ISC Konstanz has shown that such a device can also be bifacial [18] through its development of ZEBRA technology. Even if an IBC cell yields a better front efficiency than a PERT cell, some studies have reported that this is no longer the case when an albedo is considered.

Sanyo-Panasonic was the first company to market bifacial modules, which were based on its heterojunction with intrinsic thin layer (HIT) technology. This cell concept, grounded on a low-temperature process, is very well suited to the fabrication of high-efficiency bifacial cells. Indeed, the cell structure is made of very thin, hydrogenated, amorphous silicon layers (5–15nm) deposited on both sides of the wafer [19]. This technology presents many advantages:

- The band-gap difference between a-Si:H and c-Si leads to an excellent surface passivation, resulting in very high V_{oc}
- The complete process is performed at a low temperature: ~200°C
- The cells show an excellent temperature coefficient: P_{max} (–0.3%/°C)
- This symmetrical structure is compatible with thin substrates
- The fabrication process requires a limited number of fabrication steps

Finally, the efficiency potential in production is greater than 22%. On a lab scale, Sanyo-Panasonic has reported a record certified efficiency of 24.7% on $100cm^2$ [20].

Unlike the PERT approach, this technology is not highly compatible with existing production lines. As the efficiency is driven by the very high V_{oc},

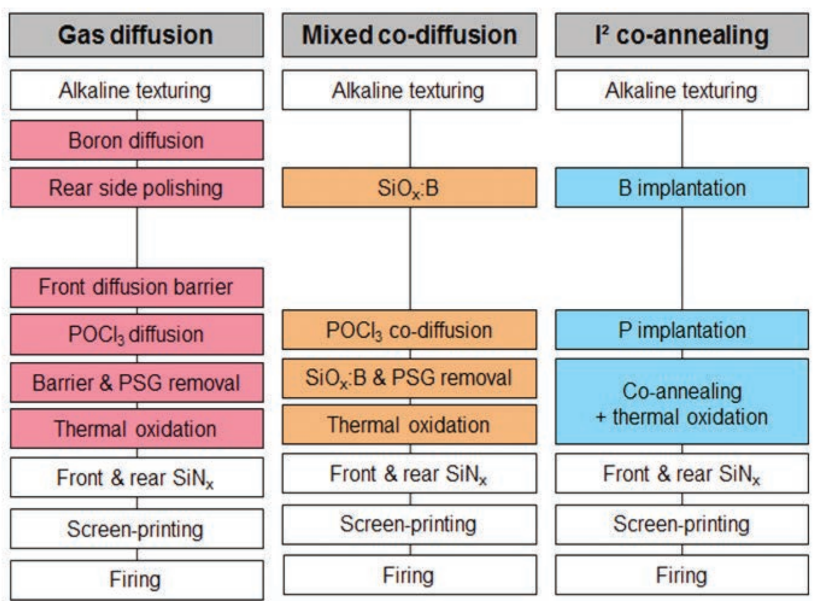


Figure 4. Examples of different process flows for the fabrication of PERT cells.

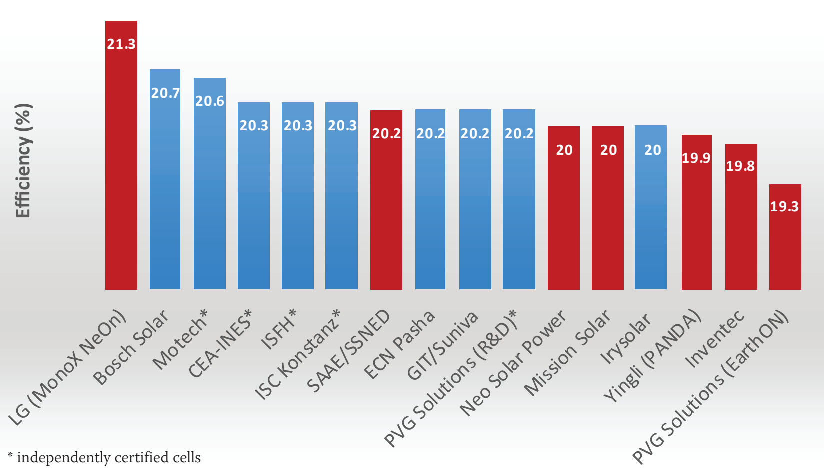


Figure 5. Reported efficiencies for bifacial PERT cells. (The red bars correspond to the performance of a PERT cell in mass production.)

the substrate quality is also very critical. Some studies have reported that a difference of 1% abs. in efficiency could be obtained over an entire ingot, leading to a widespread or specific selection of the wafers. This is largely explained by a consequent effect of interstitial oxygen content and related defect distribution, as well as the effect of thermal donors. Although Sanyo-Panasonic has for many years been the only producer of HJT cells, with a production capacity of 900MW, new players demonstrating impressive results are now emerging: Table 2 summarizes the main players in the field [21,22].

Bifacial module design considerations

Apart from a higher energy output, bifacial solar modules offer inherent advantages compared with standard, monofacial modules. Usually, bifacial modules are available as a glass substrate or, in certain cases, with a transparent backsheet foil substrate. Backsheet foils typically have a certain water permeability, allowing water to penetrate the backsheet and enter the interior of the solar module. Glass, on the other hand, will totally prevent water from penetrating the module interior over the large area of the solar module back side, which will in turn inhibit any degrading effects over time, such as oxidation or delamination. The only region not protected in glass–glass modules is the edge area, which is typically sealed by double adhesive tape, a silicone seal or specially designed edge seal getters. The solar cells themselves are protected by the large distance between module edge and cell, and any water penetration has to diffuse from the edge before degradation can take place. The advantages of glass–glass modules are best exploited when using encapsulants that do not contain or produce any chemical components that degrade cell metallization or interconnections, such as peroxides, or acetic acids in the case of EVA encapsulants.

Another advantage of glass–glass modules is their greater flexibility, notably when using thin 2mm glass, as well as their mechanical robustness as a result of the solar cells being positioned in the neutral mechanical plane of the material sandwich, hence securing the cells against mechanical tensile or compressive stress. Since the mechanical stability is significantly increased for glass–glass modules, compared with glass–foil modules, frameless applications become the preferred mounting design. This favours direct applications in building-integrated photovoltaics (BIPV) and reduces system costs. Frameless designs may also minimize the risk of potential-induced degradation (PID) in systems with a high operating voltage, as the driving force for PID is the potential between the grounded frame and the cells.

The key challenge for bifacial solar modules is the design and placement of the junction box. Since any placement of junction boxes on light-sensitive areas on the module back side leads to undesired shading, the junction box either has to be reduced in size or must be placed in the edge region of the module, if module size is to be kept constant. At the same time, these smaller junction boxes have to handle higher currents because of the extra current generated by the module back side. The latter problem can be solved by cutting the cells in half, thereby reducing the cell current and, at the same time, the cell-to-module losses. Alternatively, these cell-to-module losses could be reduced by

Company	Cell area [cm^2]	Record efficiency [%]	Status
Sanyo-Panasonic	148	21–22	900MW production
Chochu	243	22.3	Production line in Q1 2015
Kaneka	171	24.2	Production line in 2015
AUO	239	23.1	Pilot line (BenQ)
Silevo	239	23.1	100MW in production Expansion plan 1GW 2016
R&R	239	22.1	Laboratory
CEA-INES	239	22.0	Pilot line (35MW)

Table 2. Record cell efficiencies achieved with heterojunction technology.

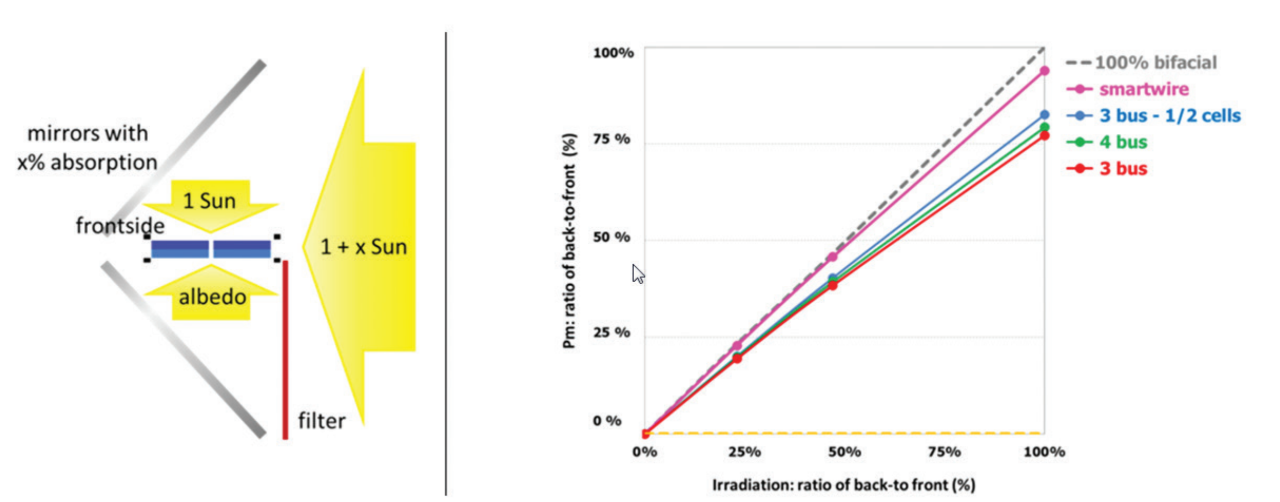


Figure 6. Gain in power P_m with a front-side irradiation of 1000W/m^2 and increasing back-side irradiation from 0 to 1000W/m^2, for different interconnection options (as measured in a solar simulator with symmetrical mirrors for simultaneous irradiation of front and back sides and a mesh filter to vary the back-side irradiation). SWCT and three bus half-cells were found to perform best [24].

an additional busbar at the cell level. A combination of both options leads to almost zero electrical losses from cell to module. This development has currently been implemented in standard glass-backsheet modules in order to further reduce costs by increasing module power, and is an attractive option for bifacial modules as well. Another interconnection option found to be very beneficial for bifacial cells and modules is SmartWire Connection Technology (SWCT) [23], which offers the best performance in a comparison of different interconnection options shown in Fig. 6 [24].

The assembly of bifacial modules by cutting the cells in half can also optimize the energy contribution of the module back side by making it less sensitive to non-uniform irradiation of the back-side surface in ground-mounted systems at low elevations.

> "Bifacial cells offer the potential to realize a significant reduction in the complexity of the cell interconnection process."

For bifacial solar cells the rear side consists of a similar finger/busbar grid to that of the front side (unlike standard, monofacial cells, in which the cell rear side is fully metallized). This makes the cells transparent to IR radiation and may lead to lower operating temperatures in the field. It also affects temperature distribution during soldering and this requires modification of the soldering time and temperature to obtain an optimal compromise between defect generation (cracks) and adhesion strength of the copper ribbons.

Bifacial cells offer the potential to realize a significant reduction in the complexity of the cell interconnection process. A simplification can be achieved by reversing the neighbouring cell so that the interconnection ribbon does not have to make a cross-over from the front to the back side, as illustrated in Fig. 7 [25]. This will allow an increase in productivity of the tabbing/stringing process, a reduction in cell spacing and, at the same time, an increase in module reliability in withstanding thermomechanical stresses caused by temperature cycling (typically tested from –40°C to +85°C). This concept of 'planar' interconnection requires cells with a high bifaciality factor (> 98%).

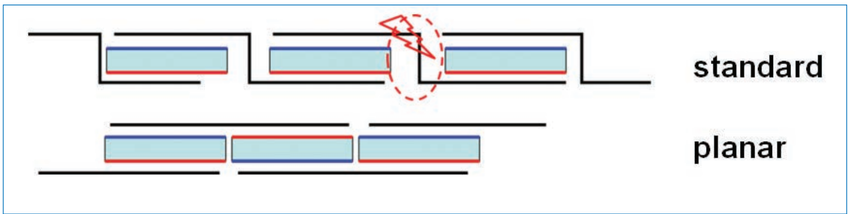


Figure 7. Top: standard cell interconnection, where the interconnection ribbons (black) connect the cell front side to the neighbouring back side. Bottom: planar interconnection process with bifacial cells.

Bifacial systems and applications

Bifacial modules can be implemented in PV systems in various ways, resulting in different bifacial gains as a result of variations in the albedo of the surroundings and the bifaciality factors of the modules: examples for ground-mounted and flat-rooftop systems are shown in Fig. 8. Systems with a module inclination (slanted) that is optimum in the case of monofacial modules result in the highest total energy production and, accordingly, in the lowest LCOE. Depending on the geographical location of the installation site and on the albedo of the underlying surface, horizontally mounted systems can also yield a high energy production.

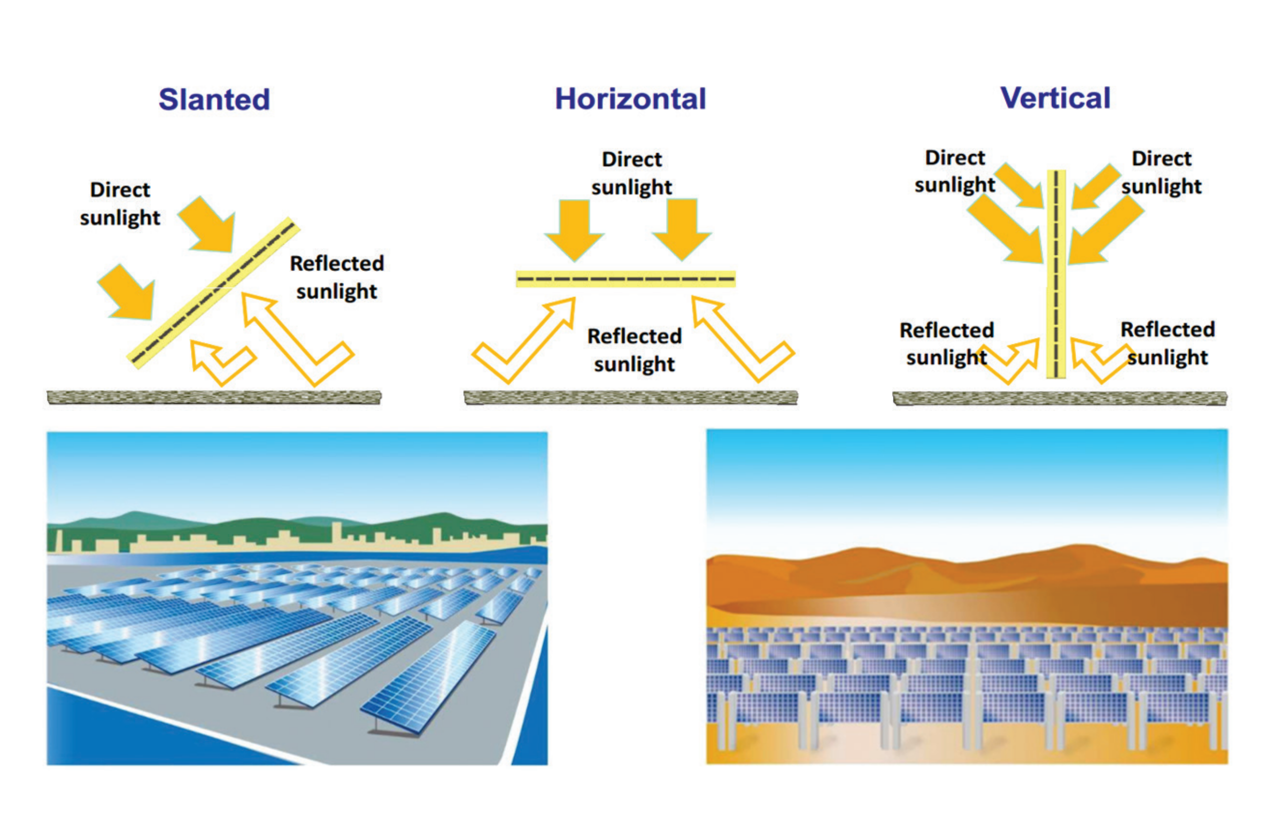
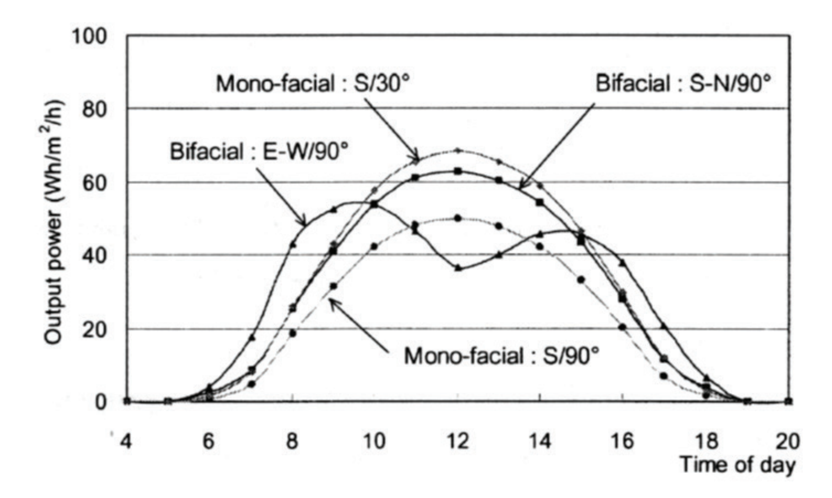


Figure 8. Different implementations of bifacial modules (landscape pictures taken from PVG Solutions [26]).

Vertical mounting has some interesting features. First, soiling is considerably reduced compared with that of modules mounted with a standard inclination, and is of particular interest for desert regions. Second, vertically mounted bifacial modules can be installed, for example, along highways or used for other applications where long single rows of modules are suitable (e.g. anti-noise barriers). Third, vertical modules facing east–west deliver the same energy yield (kWh/kWp_{front}) as south-facing monofacial modules mounted with a standard tilt. In addition, the east–west configuration of vertical bifacial modules has another interesting advantage: during the day two peaks of energy production are delivered – one in the morning and one in the evening – with a lower energy production at noon. As shown in Fig. 9, a combination of this configuration with standard, south-facing modules contributes to a more homogeneous electricity generation profile during the day ('peak-shaving') and is extremely beneficial in terms of integrating more PV power into the electricity grid.

As shown in Fig. 10, when bifacial modules are installed over surfaces with good or high reflectivity, bifacial gains (percentage increase in $kWh/kWhp_{front}$ of bifacial modules compared with kWh/kWhp of monofacial modules) of 15–26% are possible. This has a significant impact on the dimensions of the PV system: assuming a bifacial gain of 20%, and taking a traditional 1MW ground-mounted system composed of 250Wp multicrystalline modules as a reference, bifacial modules with a P_{mpp} (front) of 290Wp under front-side illumination enable the number modules to be reduced by around 30% while maintaining the same yearly electricity production (Fig. 11). Apart from reducing the amount of land required to install a PV plant with a given electricity production capacity, this also results in cost savings in all other area-related BOS costs: mounting structures, cables, and the preparation and maintenance of the installation site. As a result, bifacial PV technology allows a significant reduction in LCOE, compared with monofacial high-efficiency technologies, such as PERC.



Source: Joge et al. [27].

Figure 9. Electricity generation profile for vertically mounted (90 degrees) bifacial and monofacial modules in east–west and south exposures, compared with the generation profile of a standard configuration (monofacial, south-facing, 30-degree inclination).

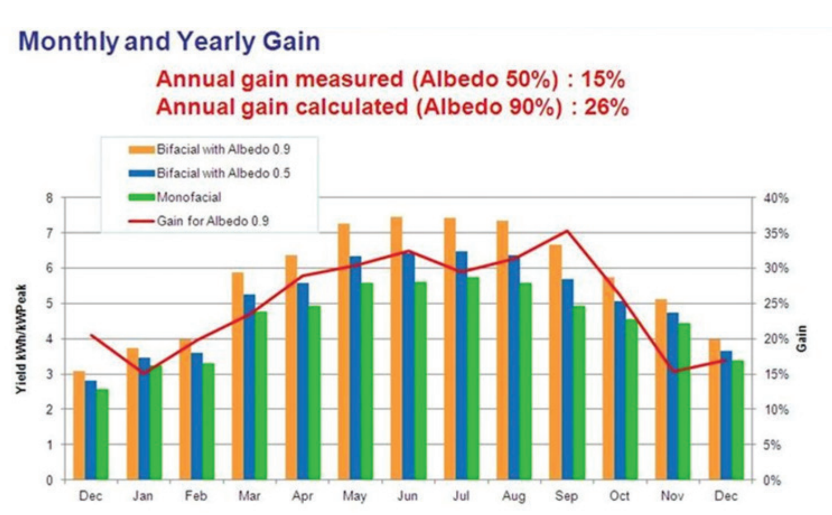


Figure 10. Bifacial gain for a PV system mounted on a flat rooftop, considering albedos of 0.5 and 0.9 [28].

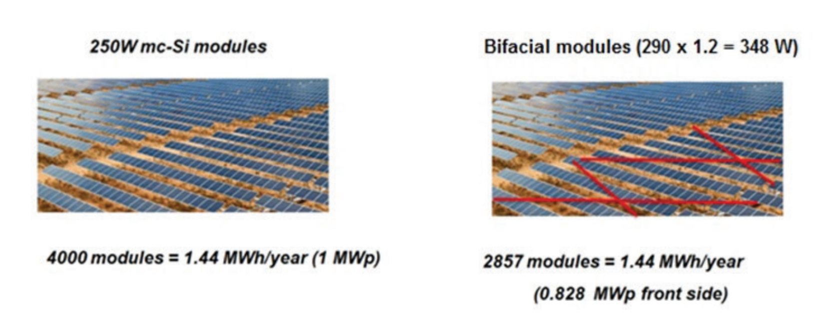


Figure 11. The use of bifacial modules requires around 30% fewer modules (for the same total kWh/year) and reduces the area-related BOS costs of the PV system.

Standardization of measurements, module qualification and system simulations

Standardization of measurements: cell and module

In most laboratories, PERT cells are measured on a gold-plated chuck, which tends to represent the optimal cell performance. As shown in Table 3, the efficiency can vary depending on the measurement method used: there is no real 'true value' – this will depend mainly on the module technology. In the case of bifacial cells intended for a bifacial module (glass–glass), measurements taken in bifacial mode (probes at the back with no light reflection) are the most suitable.

The bifacial performance of a bifacial cell can be estimated by determining the ratio of the measurements of the rear-side efficiency and the front-side efficiency in standard test conditions (STC): this gives the 'bifaciality factor'

Ref	Measure	V_{oc} [mV]	J_{sc} [mA/cm^2]	*FF* [%]	*Eta* [%]
CEA*	Conductive chuck	639.5	39.1	79.5	19.9
	Bifacial mode	639.1	38.6	79.0	19.5
ISFH*	Conductive chuck	658.0	38.6	80.0	20.3
	Bifacial mode	657.0	38.2	79.5	20.0

* Measurements at both institutes produced the same results.

Table 3. Certified efficiency of bifacial cells measured in two different configurations.

(BF), i.e. BF = η_{rear}/η_{front}. Depending on the technology and the wafer quality, this BF factor can vary from 87% to 95%, according to the range of values reported in the literature. There is current debate in the community whether in fact this BF factor represents a relevant characterization method, since under working conditions, light arrives at both sides of the cells simultaneously, with a light power density of over 1000W/m^2. New *I–V* measurement systems are now being adapted for making bifacial measurements, where the solar cell is illuminated on both sides, with various power densities ranging from 0 to 1000W/m^2.

Figure 12. ISC Konstanz's measurement site in El Gouna, Egypt.

"A major hindrance to the proliferation of bifacial products currently seems to be a lack of standardization."

A major hindrance to the proliferation of bifacial products currently seems to be a lack of standardization. The pricing of a solar product is typically done on the basis of its peak power output under STC, rated in Wp. Other cell and module parameters – such as the temperature coefficients or the weak light performance – play only a minor role when it comes to pricing.

Bifaciality, until now, has not played any role at all in standardization, because it is not considered by state-of-the-art solar simulators with single flashbulbs, when measuring the peak power under STC conditions. The light source is typically placed far enough away from the measurement subject to achieve a sufficiently homogeneous illumination in the measurement plane. The housing at the sides and behind the subject is completely black so as not to compromise the illumination homogeneity. For bifacial devices, this results in very artificial conditions – a solar device in the middle of a black cavity, which is highly unlikely to be the case in any application. Indirect irradiance caused by scattering in the atmosphere and reflections of surrounding objects is completely masked.

The focus on STC conditions creates the absurd situation that, for a module producer selling its products on a Wp basis, it is advantageous to encapsulate bifacial solar cells with a white backsheet in order to increase the STC value because of internal reflections behind the cell and in the spacing between the cells. However, the user of the device would, in almost every application, harvest more kWh/year with the same module if a transparent backsheet were chosen.

Some companies compensate for the above-mentioned deficiency by quoting the *I–V* parameters both under STC conditions and under a range of conditions with varying additional rear illumination. Others quote *I–V* parameters under illumination conditions defined by the resulting I_{sc} increase as a percentage of the I_{sc} under STC. Some of these datasheet values seem to be measured, whereas others appear to be extrapolated. Details of the data and their determination are usually not quoted.

In summary, it is difficult for a consumer to compare these products and even more difficult to contrast them with monofacial alternatives.

Qualification: module

Since, in an installation with bifacial illumination, the maximum operating current of the module is increased, qualification entities ask themselves how the severity of qualification tests should be increased in order to take into account the rear-side current. Ideally these tests should reflect worst-case operating conditions, which can differ significantly from STC for installations with high albedo. TüV Rheinland therefore proposed to modify the current-driven tests to a current that is equivalent to 400W/m^2 of additional rear-side irradiation [29].

The same applies in the case of the electrical designer of a bifacial installation, who must also consider the increased currents when defining the wire dimensions, the appropriate inverter and protection devices. The designer's job is at least facilitated by the fact that the maximum albedo of a specific installation can be easily measured or estimated from tabulated values.

An accurate calculation or simulation both of the annual energy yield gain of a bifacial installation and of the performance of the system for each position of the sun depends on the spatial distribution of the rear irradiance, which is significantly affected by the geometric conditions of the specific installation [30].

Many bifacial test installations achieve high bifacial gain in conditions characterized by a low zenith angle of the sun, partial overclouding and high indirect irradiance. This explains why the annual yield gain is often higher than the maximum power gain on a sunny day.

In order to achieve a standardization of certification measurements, data sheet declarations and test conditions, and to connect these to maximum current and yield simulations, it was decided by a group of institutes, test laboratories, equipment manufacturers and producers of bifacial solar products during the latest bifacial workshop to establish four working groups addressing all standardization topics [1]. The first meeting took place at the EU PVSEC, in which the participants agreed on a roadmap for the next few steps.

Simulations: systems

It has also already been demonstrated at large-scale solar power plants that the energy yield of a solar system can be significantly enhanced by the use of bifacial modules [14]. In the desert at El Gouna (Egypt), ISC Konstanz compared a bifacial module with a monofacial module [31], both containing n-type screen-printed solar cells of similar technologies [32,33]. For both modules, the tilt angle was 20 degrees, the lower edge was 1m high and the front sides were facing south (Fig. 12). Fig. 13 shows the percentage gain in energy yield in terms of kWh/kWp in the first eight months of 2014 of the BiSoN bifacial module over the ^{n}Solar monofacial module. The overall average gain was as high as 22.3%, and in August an average monthly gain of 25.6% was recorded.

A second bifacial module, namely the ^{n}Solar bifacial module, with a BF of only 55%, was also installed at El Gouna. Fig. 14 shows its power output on May 15th, 2014, along with the irradiance throughout the day; a peak power output as high as 426W was recorded.

bSolar has developed a simulation tool for its bifacial module technology, whereby the electrical gain is calculated as a function of installation height, packing density and albedo, as shown in Fig. 15. For example, a very densely packed system, with an installation height of 1m and an albedo of 50%, can yield a yearly electrical gain of more than 20%.

Commercialization and outlook

As already mentioned, glass–glass modules are rapidly entering the market, as they offer several advantages over standard monofacial modules with white backsheets. Module manufacturers using this technology (SiModule, Apollon Solar, etc.) are therefore screening the market for bifacial solar cells which can be manufactured the same way as standard cells. Currently, there are only

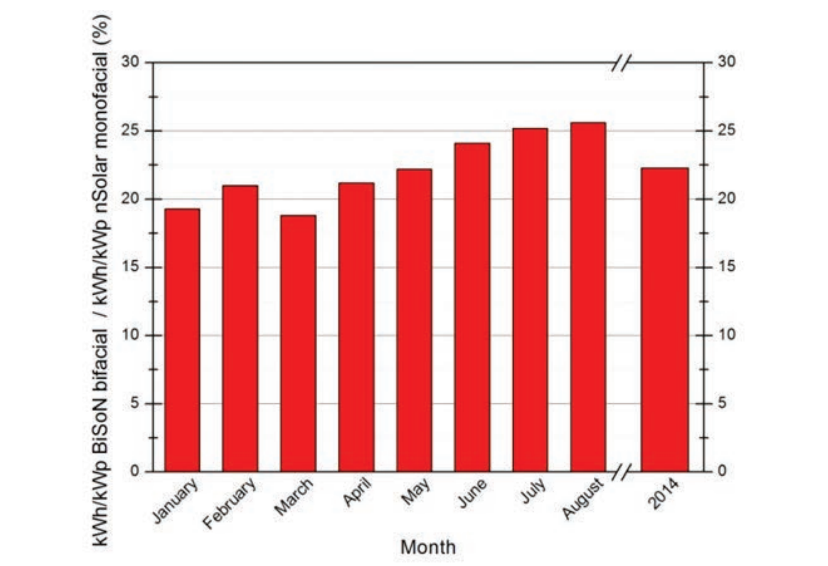


Figure 13. Percentage gain in kWh/kWp energy yield in 2014 of the BiSoN bifacial module over the ^{n}Solar monofacial module.

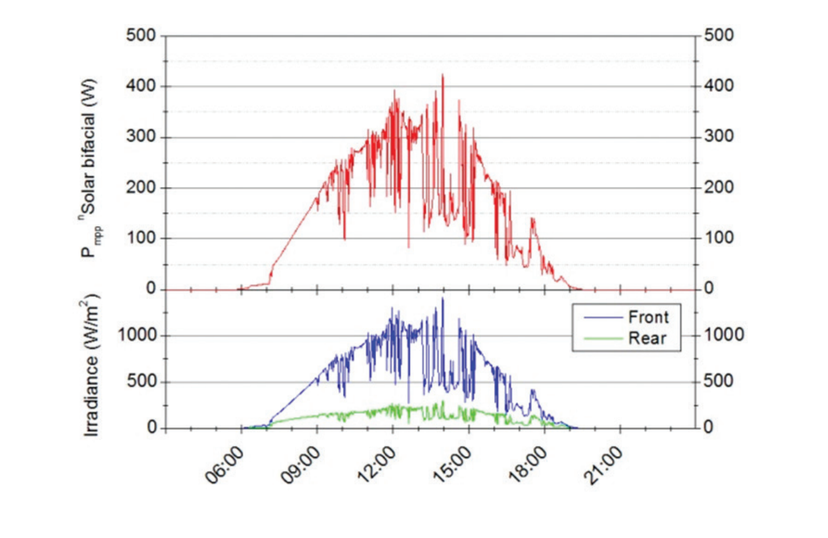


Figure 14. Irradiance and power output of the ^{n}Solar bifacial module at El Gouna on May 15th, 2014.

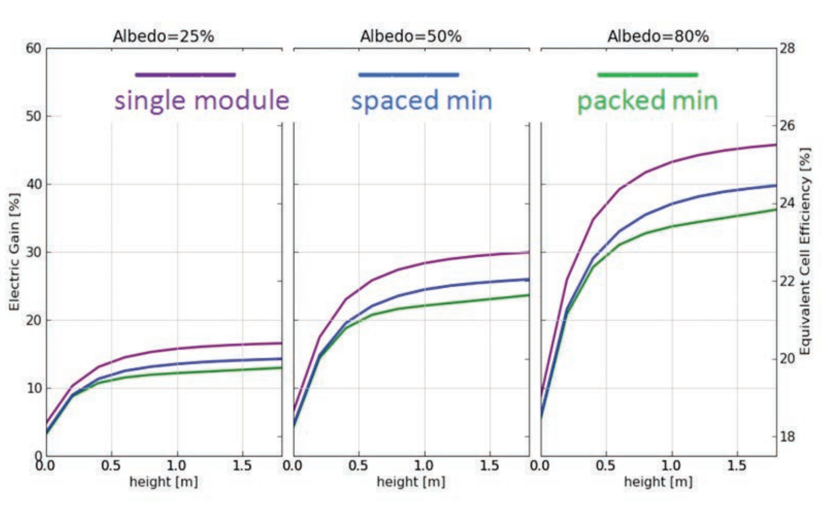


Figure 15. Simulations by bSolar of yearly electrical gain of south-facing bifacial PV installations as a function of installation height, packing density and albedo.

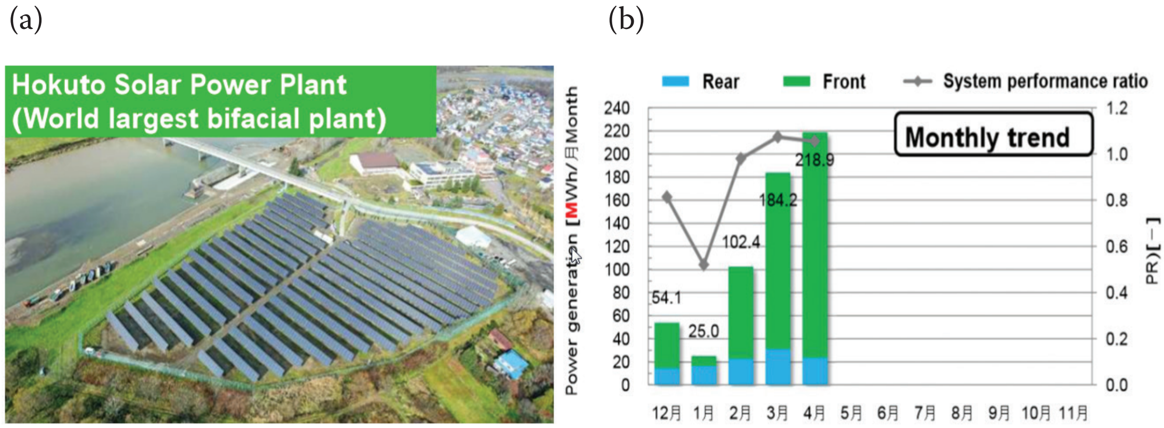


Figure 16. (a) Aerial view of the world's largest bifacial PV plant; (b) monthly energy contribution from the rear.

a few possibilities, such as those offered by PVG Solutions and NeoSolarPower (NSP); the newcomers MegaCell, Motech and Mission Solar Energy will offer bifacial solar cells in Q1/Q2 2015. Panasonic, Silevo and Sunpreme currently market bifacial modules, and First Solar will most likely follow next year as well.

Manufacturing equipment suppliers and technology transfer companies who offer bifacial cell and module technologies are the n-PASHA Alliance (Tempress, RENA, ECN), BiSoN Alliance (centrotherm, ISC Konstanz), French companies supported by INES (ECM Greentech, SEMCO Engineering), Schmidt and Meyer-Burger.

> "Large bifacial power plants will be an important part of worldwide PV electricity generation in the future."

To summarize, it has been shown that it is now time to take the step towards bifaciality and that standardization and system simulations are necessary in order to support a sustainable market penetration. The authors are confident that large bifacial power plants will be an important part of worldwide PV electricity generation in the future – plants similar to the largest one at present from PVG Solutions in Japan, shown in Fig. 16.

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About the Authors

Dr. Radovan Kopecek, one of the founders of ISC Konstanz, has been working at the institute as a full-time manager and researcher since January 2007, and is currently the head of the Advanced Solar Cells Department. Dr. Kopecek has also been teaching the basics of PV at the DHBW in Friedrichshafen since 2012. He received his master's degree from Portland State University (Oregon, USA) in 1995, and then obtained his diploma in physics from the University of Stuttgart in 1998. He completed his Ph.D. in 2002 in Konstanz, with a dissertation topic of thin-film silicon solar cells.

Dr. Yannick Veschetti joined CEA-INES in 2005 and is currently responsible for the homojunction silicon solar cells laboratory. He studied at Strasburg University and received his Ph.D. in physics in 2005. Dr. Veschetti specializes in the field of crystalline silicon PV, with his main R&D work focusing on the development of solar cells technology on n-type silicon.

Dr. Eric Gerritsen has been a project leader in PV modules at CEA-INES since 2008, working on module reliability and performance. Before joining INES he spent 23 years in various positions with Philips Research Laboratories, Philips Lighting and Philips Semiconductors/NXP in the Netherlands, Germany and France. He received a Ph.D. in the field of ion implantation from the University of Groningen in the Netherlands.

Dr. Andreas Schneider received his diploma in physics from the University of Freiburg in 1999 and his Ph.D., with a thesis topic concerning crystalline silicon solar cells, from the University of Konstanz in 2004. He then worked at the University of Konstanz, where he was responsible for the development of crystalline silicon solar cells. From 2005 to 2011 he was employed at Day4Energy, first as the head of R&D and then as the director of the company's quality management department. At the beginning of 2011 Dr. Schneider worked for a short while at Jabil, before joining ISC Konstanz as the head of the module development department.

Corrado Comparotto obtained his M.Sc. in electronic engineering in 2008 from the University of Brescia in Italy. Since March 2011 he has been working on bifacial n-type solar cells in the Advanced Solar Cell Concepts department at ISC Konstanz.

Dr. Valentin D. Mihailetchi joined ISC Konstanz in 2008 and is currently a senior scientist, leading the n-type solar cells group in the Advanced Cell Concepts department. He studied at the University of Groningen in the Netherlands; in 2005 he received his Ph.D. in physics, with the device physics of organic solar cells as his thesis topic. After that, Dr. Mihailetchi worked as a research scientist on crystalline silicon at ECN Solar Energy in the Netherlands, where he developed n-type-based solar cell processes for industrial applications.

Jan Lossen studied physics at the University of Freiburg and the University of Cologne, graduating in 2003 with a diploma thesis concerning microcrystalline silicon layers. He worked on the production and development of PV products for more than 10 years at ErSol Solar Energy AG and later Bosch Solar Energy AG. Since June 2014 Jan has been a project manager in the Industrial Solar Cells department at ISC Konstanz, where he is responsible for transferring BiSoN technology from laboratory to industrial production.

Dr. Joris Libal works at ISC Konstanz as a research engineer, focusing on business development and technology transfer in the areas of high-efficiency n-type solar cells and innovative module technology. He received a diploma in physics from the University of Tübingen and a Ph.D. in the field of n-type crystalline silicon solar cells from the University of Konstanz. Dr. Libal has been involved in R&D along the entire value chain of crystalline silicon PV for more than 10 years, having held various positions at the University of Konstanz, at the University of Milano-Bicocca and, more recently, as the R&D manager at the Italian PV module manufacturer Silfab SpA.

Enquiries

ISC Konstanz
Rudolf-Diesel-Straße 15
78467 Konstanz
Germany

Tel: +49-7531-36 18 3-22
Email: radovan.kopecek@isc-konstanz.de
Website: www.isc-konstanz.de

Simplifying the fabrication of n-PERT solar cells: Recent progress at ISFH

Bianca Lim[1], **Fabian Kiefer**[1], **Nadine Wehmeier**[1], **Till Brendemühl**[1], **Yevgeniya Larionova**[1], **Frank Heinemeyer**[1], **Jan Krügener**[2], **Robby Peibst**[1] & **Thorsten Dullweber**[1]

[1]Institute for Solar Energy Research Hamelin (ISFH), Emmerthal; [2]Institute of Electronic Materials and Devices, Leibniz University of Hanover, Germany

ABSTRACT
In this paper large-area (239cm^2) n-type passivated emitter, rear totally diffused (n-PERT) solar cells are compared with state-of-the-art p-type passivated emitter and rear cells (p-PERC) to evaluate potential advantages of n-PERT over p-PERC. In particular, an investigation has been carried out of fully screen-printed bifacial n-PERT solar cells, in which the boron-doped emitter is contacted with aluminium-containing silver (AgAl) pastes, as well as of n-PERT back-junction (BJ) solar cells, in which the B-doped emitter is locally contacted with screen-printed Al. Using two separate quartz furnace diffusions for the B- and P-doped regions, efficiencies of up to 20.3% on bifacial n-PERT solar cells and of up to 20.5% on n-PERT BJ solar cells were achieved. In comparison, reference p-PERC solar cells that were processed in parallel achieved efficiencies of up to 20.6% before light-induced degradation (LID), but degraded to 20.1% after 48 hours of illumination. In addition, ion implantation and pre-deposition of dopant sources have been evaluated as alternative technologies for forming the full-area doping of the front and rear wafer surfaces, thus reducing the number of processing steps for n-PERT solar cells. Using ion implantation and a co-annealing step, efficiencies of up to 20.6% for bifacial n-PERT solar cells have been achieved, and of up to 20.5% for n-PERT solar cells, in which the P-doped back-surface field is contacted with evaporated Al. By employing a boron silicate glass (BSG) deposited via plasma-enhanced chemical vapour deposition (PECVD) as a dopant source, along with a co-diffusion step, n-PERT BJ solar cells have been fabricated with up to 19.8% energy conversion efficiency.

Introduction
The majority of crystalline silicon solar cells are currently fabricated on boron-doped (B-doped) p-type silicon. However, forecasts – such as the ITRPV Roadmap [1] – predict that the share of phosphorus-doped (P-doped) n-type silicon will increase in coming years. One advantage of P-doped n-Si is the absence of light-induced degradation (LID) of the carrier lifetime, which is associated with the simultaneous presence of boron and oxygen in p-Si [2]. In addition, the most common metal impurities – such as iron – are less harmful in n-Si, resulting in significantly higher minority-carrier lifetimes in n-type Czochralski-grown silicon (Cz-Si) [3]. As a consequence, high-efficiency solar cell concepts – such as interdigitated back-contact (IBC) or silicon heterojunction (HJT) cells – often use n-Si wafers [4,5].

> "Forecasts predict that the share of phosphorus-doped (P-doped) n-type silicon will increase in coming years."

With regard to upgrading existing production lines for screen-printed p-type silicon solar cells to production lines for n-Si solar cells, the IBC and HJT technologies both use processing tools which are different from those for standard p-type solar cells, and which potentially require a rather large investment in new equipment. The n-type passivated emitter, rear totally diffused (n-PERT) or passivated emitter, rear locally doped (PERL) concepts, on the other hand, use similar processing steps and tools to those for standard p-type solar cells, and hence should require only little, if any, tool-conversion investment.

A number of variations of the n-PERT solar cell have been proposed. Laboratory-type small-area cells (4cm^2) with a B-doped front-side emitter and a P-doped back-surface field (BSF) have achieved efficiencies of up to 22.7% [6], demonstrating the high efficiency potential of the n-PERT concept. A more industrially feasible alternative is a screen-printed bifacial structure, which is shown schematically in Fig. 1(a). The bifacial n-PERT solar cell has already been commercialized [7] and is currently the most intensively studied n-PERT structure [8–10]. Both sides of the solar cell are textured and the two highly doped regions may be contacted via screen printing, in which silver (Ag) pastes are used for the P-doped BSF and aluminium-containing Ag pastes (AgAl) are used to contact the B-doped emitter. Efficiencies of up to 20.5% have been reported for an ion-implanted, fully screen-printed 239cm^2 solar cell utilizing this structure [10].

Besides the advantage of a potentially lean process flow, the bifacial n-PERT concept could offer the advantage of harvesting additional light from the rear side, which may result in an enhanced energy yield. A potential disadvantage of this structure is that silver consumption is higher than that for a standard p-type solar cell, most of the rear side of which is metallized by screen-printed Al. One possible method of reducing Ag consumption is the deposition of Al via physical vapour deposition (PVD) on the rear side [11,12], as shown in Fig. 1(b). Another possibility is an n-PERT back-junction (BJ) solar cell, since the B-doped emitter, in contrast to the P-doped BSF, can also be contacted with screen-printed Al paste; a schematic of the structure is shown in Fig.1(c). The n-PERT BJ solar cell has a strong resemblance to a p-type passivated emitter and rear cell (p-PERC), both in architecture and in processing sequence, potentially facilitating its implementation in p-PERC production lines. The usage of AgAl paste to contact B-doped emitters can also result

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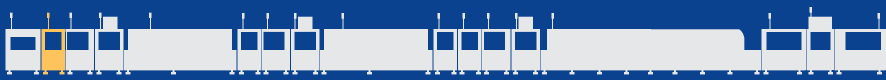

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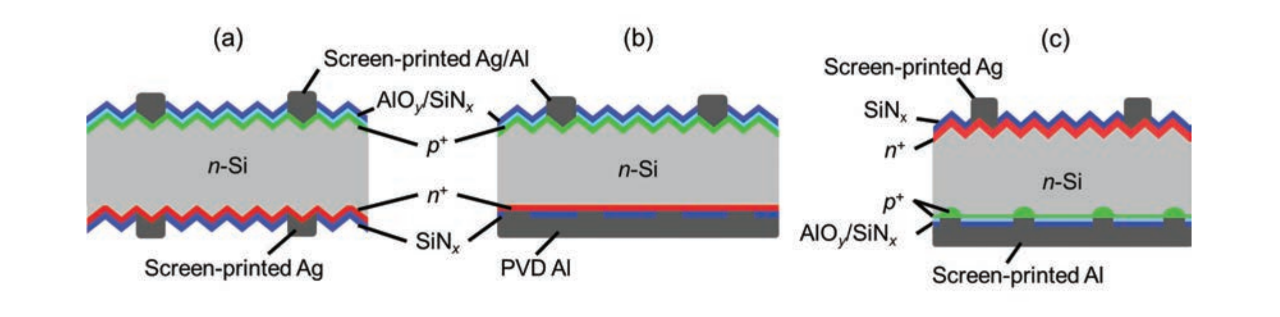

Figure 1. Schematics of (a) bifacial n-PERT solar cell; (b) front-junction n-PERT solar cell with evaporated Al on the rear side; and (c) n-PERT BJ solar cell. The Al on the rear side can be either evaporated or screen printed.

in significant V_{oc} losses [13], which would be avoided in the n-PERT BJ concept. Indeed, the highest large-area (239cm^2) n-PERT efficiency reported so far of 21.3% was achieved with an n-PERT BJ solar cell featuring PVD Al rear-side metallization [14]. For a fully screen-printed version of this cell concept, a maximum efficiency of 20.7% has been reported so far [14].

The n-PERT structure can be modified to create an n-PERL structure, in which only localized P-doped regions are formed. In this case, the wafer itself has to provide a certain lateral conductivity for the electrons, which implies stronger restrictions on the base resistivity than for the n-PERT concept. However, one advantage of the n-PERL concept is the decoupling of the doping level required for low contact resistance in the metallized regions from the level required for low Auger and Shockley-Read-Hall surface recombination in the passivated regions.

A major manufacturing challenge of the n-PERT solar cell is the formation of two different full-area highly doped regions at the front and rear wafer surfaces. In laboratory processing, a popular method is to use two separate quartz furnace diffusions, where dielectric layers are used as diffusion barriers. However, since these layers are sacrificial, this processing sequence is rather complex for production; alternative doping techniques might thus be required in order to successfully transfer n-PERT technology to mass production.

In this paper, two doping techniques for achieving different front- and rear-surface diffusions are discussed: 1) ion implantation, and 2) doping from a pre-deposited boron-containing silicon oxide layer (boron silicate glass – BSG). Both techniques are inherently single sided and may be optimized to require only one high-temperature step. Saturation current densities J_{0e} of the resulting B-doped regions are reported as well as the energy conversion efficiencies of solar cells which were fabricated using these techniques. Regarding the investigated cell concepts, recent R&D results of n-PERT front-junction structures (either bifacial or with PVD Al rear-side metallization), n-PERT BJ and n-PERL solar cells are presented. When sequential quartz furnace diffusions are used, energy conversion efficiencies of up to 20.5% for n-PERT BJ solar cells are achieved. With ion implantation and a co-annealing step, the efficiencies achieved are up to 20.6% for fully screen-printed bifacial n-PERT cells and up to 20.5% for n-PERT cells with PVD metallization of the P-BSF.

Reference n-PERT solar cells using two separate diffusions

To evaluate the potential of new processing technologies such as ion implantation and pre-deposition of dopant sources, two reference processing sequences are established, one for bifacial n-PERT solar cells and the other for n-PERT BJ solar cells. Both reference processes use two separate quartz furnace diffusions and the application of dielectric protection layers to form the two different full-area doped regions on the front and rear sides of the wafer. In addition, both reference processes use screen printing to contact both the front and rear sides of the solar cell.

For the bifacial solar cells, P-doped Cz-Si wafers with a resistivity of 5–6Ω·cm and an area of 239cm^2 are used. The processing sequence includes saw damage removal in KOH, alkaline texturing of the front and rear surfaces, a BBr_3 boron diffusion, a $POCl_3$ phosphorus diffusion, and the application of sacrificial dielectric layers prior to the two separate diffusions. The P-doped rear side of the solar cell is passivated with plasma-enhanced chemical vapour deposited (PECVD) silicon nitride (SiN_x), while the B-doped front side is passivated with a stack of atomic layer deposited (ALD) aluminium oxide (AlO_y) and PECVD SiN_x. After passivation, AgAl paste is screen printed on the B-doped emitter and Ag paste on the P-doped BSF.

Since AgAl pastes can induce high recombination on B-doped emitters [13], an evaluation of the dual-print technique for reducing the contact area of the AgAl paste with the B-doped emitter was also performed. Dual print uses a thin nickel foil as a stencil to print the contact fingers, while the busbars are printed with a conventional mesh screen. The advantage of stencil printing is that no obstructions are present in the openings, resulting in a much more homogeneous Ag finger height compared with that obtained in screen printing. At the same time, the busbars and fingers are printed in two separate steps. Although the number of processing steps is increased, dual print offers the opportunity to use two different pastes for the fingers and the busbars, and, in particular, a non-firing-through busbar paste. As a result, the area fraction of the potentially highly recombination-active AgAl contact was reduced from 7.4% to 4.1%.

The use of single screen printing for fingers and busbars has led to the realization of energy conversion efficiencies of up to 20.0% for bifacial n-PERT solar cells using two separate diffusions (measured on a reflecting chuck). With dual print, and thus non-contacting busbar pastes, energy conversion efficiencies of up to 20.3% (independently measured at Fraunhofer ISE CalLab on a reflecting chuck) have been achieved.

The reference processing sequence of n-PERT BJ solar cells is based on the high-efficiency p-PERC process detailed in Hannebauer et al. [15]. Processing steps include saw damage removal in KOH, BBr_3 boron diffusion, deposition of a dielectric layer on the rear side of the wafer, alkaline texturing (thus removing the B-doped region on the front side), $POCl_3$ phosphorus diffusion, and subsequent removal of the protection layer and phosphosilicate glass (PSG) in HF. The P-doped front side of the solar cell is passivated with PECVD SiN_x, while the B-doped rear side is passivated with a stack of ALD AlO_y and PECVD SiN_x. In order to facilitate the formation of the rear contact, the AlO_y/SiN_x stack on the rear is locally ablated (line shaped) using a picosecond

	Co-diffusion using PECVD BSG layers	Ion implantation with subsequent co-annealing
Advantages	+ Independent tailoring of P and B profile possible + Co-diffusion utilizes conventional $POCl_3$ tubes + PECVD BSG layer might be multi-functional (e.g. doping source/diffusion barrier and protection layer for single-side texturing)	+ High efficiencies up to 22.7% already demonstrated [6] + Excellent homogeneity + Silicon oxide passivation might be grown in situ during anneal + Selective emitter realizable via shadow masks + Selective BSF (PERL structure) realizable via shadow masks + (Front junction): AgAl metallization-induced V_{oc} loss less pronounced than for BBr_3 diffusion [11,17] + Edge isolation via masked implant (no additional step)
Disadvantages	- Edge isolation possibly required - Local doped structures (selective emitter, selective BSF) more challenging to realize	- Co-anneal (high temperature budget required for B anneal) complicates tailoring of P profile

Table 1. Potential advantages and disadvantages of co-diffusion using PECVD BSG layers and of ion implantation with subsequent co-annealing.

laser with a wavelength of 532nm before screen printing Ag on the front side and Al on the rear. Finally, the solar cells are co-fired. With the reference process, energy conversion efficiencies of up to 20.5% (independently measured at Fraunhofer ISE CalLab) [16] have been achieved so far.

Technologies for simplifying the n-PERT process

In parallel with the establishment of n-PERT baseline processes based on two separate quartz furnace diffusions (BBr_3 and $POCl_3$), two technologies that potentially lead to a significant process simplification of the n-PERT were evaluated: 1) co-diffusion using PECVD BSG layers as a boron source, and 2) ion implantation of boron and phosphorus, with a subsequent co-anneal of the implant damage. The potential advantages and disadvantages of both technologies are listed in Table 1 (as research institutes, we cannot comment on cost issues or on tool-related challenges).

In the case of ion implantation, several investigative groups have solved the challenge of annealing the damage induced by the non-amorphizing implant of elementary boron [12,17–20]. In the work reported in this paper, implanted boron was furnace annealed at 1050°C [12]. For p^+ sheet resistances in the range 50–100Ω/sq. on textured surfaces, saturation current densities J_{0e} of 50–80fA/cm^2 are obtained using fired AlO_y/SiN_x stacks for passivation, as shown in Fig. 2 [12]. These values, since they are as low as those obtained for BBr_3-diffusion-based B-doped emitters, indicate a sufficient annealing of implant-induced crystal defects [21].

However, during the co-annealing of B and P implants, the relatively high temperature budget required for the B anneal results in deep P profiles with low peak- and surface-doping concentrations.

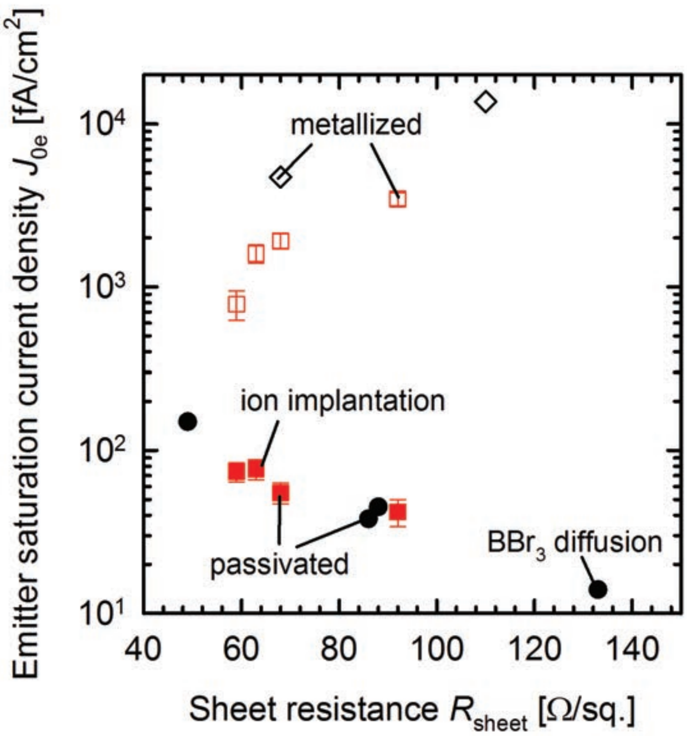

Figure 2. Emitter saturation current densities J_{0e} as a function of sheet resistance R_{sheet} on textured surfaces. Black symbols denote values for boron-diffused emitters [22,23], whereas red symbols correspond to ion implantation. Open symbols refer to metallized surfaces, and filled symbols represent passivated surfaces (fired AlO_y/SiN_x stack).

Thus, achieving low specific contact resistances with Ag screen printing on the n^+ doped regions is not trivial, although this is less of an issue because of recent Ag paste improvements. In any case, the solution is to use a sufficiently high P dose. Alternatively, PVD metallization of the n^+ doped regions also yields low specific contact resistances for relatively low surface-doping concentrations of ~10^{19}cm^{-3} [24].

For the ion-implanted and co-annealed bifacial n-PERT solar cells, a double-side texture is applied after initial wafer cleaning. A B implant on the front side and a P implant on the rear are then performed, followed by a co-annealing step. Similarly to the reference process, the rear side is passivated with PECVD SiN_x and the front side with an ALD-AlO_y/PECVD-SiN_x stack. For contacting, AgAl paste is printed on the B-doped emitter and Ag paste on the P-doped BSF. Contact formation is done in a co-firing step. Sufficiently low specific contact resistances on the P-doped BSF are obtained, even for moderate P doses, by using state-of-the-art Ag screen-printing pastes. The highest independently confirmed efficiency of 20.3% for these types of cell is identical to that for the $BBr_3/POCl_3$-diffusion-based bifacial n-PERT reference (Table 2). With further improvements, an in-house measured efficiency of 20.6% was recently achieved for ion-implanted, co-annealed and fully screen-printed bifacial n-PERT cells (Table 2).

"Sufficiently low specific contact resistances on the P-doped BSF are obtained, even for moderate P doses, by using state-of-the-art Ag screen-printing pastes."

PVD Al for contacting the P-doped BSF was also evaluated; in this case, the solar cells are only textured on the front side. After printing AgAl paste on the B-doped emitter, the solar cells are fired. Subsequently, the SiN_x on the rear side is locally ablated (point shaped) using a picosecond laser with a wavelength of 532nm, and the Al is evaporated. Finally, a short contact tempering [12] is performed. As in the case of the reference bifacial solar cells, standard screen printing of the front-side AgAl metallization was compared with dual printing using a non-contacting Ag paste for the busbars. With single screen printing, energy conversion efficiencies of up to 20.3% and a V_{oc} of 663mV were achieved; the use of dual print resulted in efficiencies of up to 20.5% and a V_{oc} of 665mV (Table 2).

Interestingly, it was observed that state-of-the-art commercial AgAl pastes induce a V_{oc} loss of only ~10mV for the ion-implanted n-PERT solar cells. This is much less than the 20–30mV reported for screen-printed metallization of BBr_3 diffused emitters [13]; this was also observed for the reference bifacial n-PERT solar cells. One possible reason for this finding is the slightly different shape of the B profiles after diffusion and after implant.

Table 2 also compares the characteristics of the reference n-PERT BJ solar cells (fabricated using two separate diffusions) with the characteristics of p-PERC solar cells, which were processed in parallel. The p-PERC solar cells used 3Ω·cm B-doped Cz-Si, which exhibits the well-known LID of the minority-carrier lifetime and thus the solar cell efficiency. As a result, the initial energy conversion efficiency of 20.6% degrades to a final value of 20.1% after illumination for 48 hours. In contrast,

	η [%]	J_{sc} [mA/cm^2]	V_{oc} [mV]	FF [%]
Reference bifacial n-PERT	20.3*	38.6*	658*	80.0*
Ion-implanted bifacial n-PERT	20.3*	38.8*	656*	79.9*
Ion-implanted n-PERT, PVD rear side	20.5*	38.8*	665*	79.5*
Ion-implanted bifacial n-PERT (late-news result)	20.6	38.9	662	79.9
Reference n-PERT BJ	20.5*	38.7*	665*	79.8*
p-PERC, 3Ω·cm	20.6	38.9	661	80.1
p-PERC, 3Ω·cm (degraded)	20.1	38.8	657	79

*independently measured at ISE CalLab

Table 2. Performance characteristics of different n-PERT and p-PERC solar cells (239cm^2), which were fabricated using conventional quartz furnace diffusions as well as ion implantation by applying the process sequences of Table 3.

A: p-PERC	B: n-PERT BJ	C: bifacial n-PERT FJ using ion implantation	D: n-PERT FJ using ion implantation and PVD Al
Wafer cleaning	Wafer cleaning	Wafer cleaning	Wafer cleaning
Rear protection layer	B diffusion BSG etch Rear protection layer		Rear protection layer
Texturing	Texturing	Texturing	Texturing
P diffusion PSG+dielectric etch	P diffusion PSG+dielectric etch	Front: B implant Rear: P implant Co-annealing	Protection layer removal Front: B implant Rear: P implant Co-annealing
Rear: AlO_y/SiN_x Front: SiN_x	Rear: AlO_y/SiN_x Front: SiN_x	Rear: SiN_x Front: AlO_y/SiN_x	Rear: SiN_x Front: AlO_y/SiN_x
Rear: laser ablation	Rear: laser ablation		
Front: Ag screen printing	Front: Ag screen printing	Front: AgAl screen printing	Front: AgAl screen printing
Rear: Al screen printing	Rear: Al screen printing	Rear: Ag screen printing	
Co-firing	Co-firing	Co-firing	Firing
			Rear: laser ablation Rear: PVD Al Contact tempering
11 steps	13 steps	10 steps	14 steps

Table 3. Process sequences for the different solar cells.

the efficiency of the n-PERT BJ solar cells remains stable at 20.5% (±0.1% is measured, which is within the measurement uncertainty).

Apart from the resulting energy conversion efficiency, the number of processing steps is also an important characteristic of a solar cell process. Table 3 gives an overview of the process sequences as described above and indicates the steps performed for the fabrication of A) p-PERC solar cells; B) n-PERT BJ solar cells using two separate diffusions; C) bifacial n-PERT front-junction (FJ) solar cells using ion implantation; and D) n-PERT FJ solar cells with full-area PVD Al on the rear side. (Common processing steps are highlighted in blue.)

When compared with the process sequence for p-PERC solar cells, the process sequence for ion-implanted bifacial n-PERT FJ solar cells (C) already seems viable, whereas the process sequences B and D probably need process simplifications to become feasible. For the ion-implanted n-PERT FJ solar cells with PVD Al on the rear side (D), for example, one-sided texturing would reduce the number of process steps by two. For n-PERT BJ solar cells (B), single-side pre-deposition of dopant sources is a very interesting alternative, as it means one high-temperature step and one dielectric etch can be removed from the process sequence.

Different deposition techniques – such as spin-on [25], PECVD [26,27] and atmospheric pressure chemical vapour deposition (APCVD) [28] – are currently being investigated for such single-side pre-depositions. Efficiencies up to 19.3% have been achieved [25] using a printable boron source and screen-printed contacts, while 19.9% has been reported for a bifacial n-PERT solar cell using APCVD BSG as the dopant source [28].

In the study reported here, BSG layers deposited by PECVD using silane (SiH_4), nitrous oxide (N_2O) and diborane (B_2H_6) as precursor gases were evaluated. Fig. 3 shows the saturation current densities J_{0e} obtained for B-doped regions as a function of sheet resistance R_{sheet}. The use of PECVD BSG layers as the dopant source results in J_{0e} values of 40–60fA/cm^2 on planar surfaces for sheet resistances between 50 and 180Ω/sq. (passivated with annealed ALD AlO_y). These values are a factor of two to five higher than those reported for planar BBr_3 diffused samples passivated similarly (indicated by the black symbols); however, the difference is smaller at moderate sheet resistances around 90Ω/sq. In addition, the sheet resistance of the PECVD BSG B diffusion is adjustable over a wide range by varying the composition and thickness of the PECVD BSG as well as the drive-in conditions [26,29]. When the BSG layer is deposited on the rear side of the solar cell after saw damage removal, it can also serve as a protection layer during the subsequent front-side texturing step. This multi-functionality further reduces process complexity, especially for n-PERT BJ solar cells.

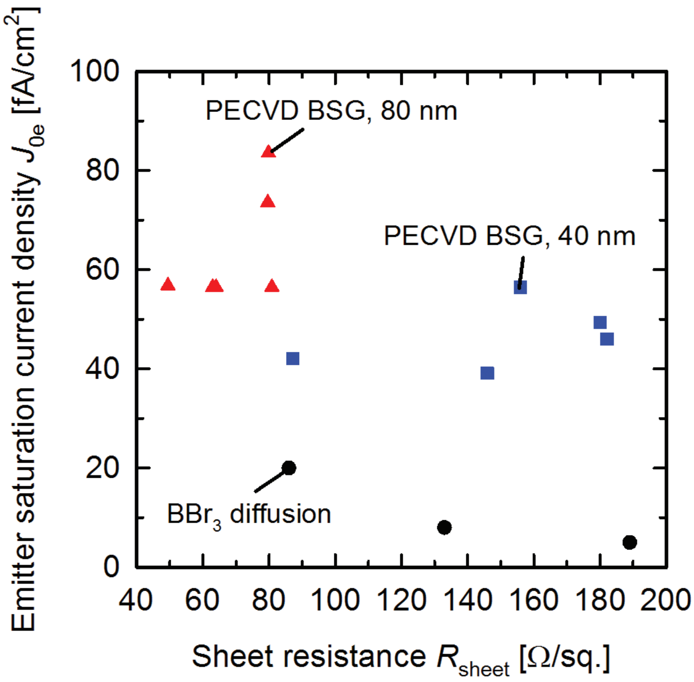

Figure 3. Emitter saturation current densities J_{0e} of boron diffusions on a planar surface passivated with annealed ALD AlO_y as a function of sheet resistance R_{sheet}. The black circles represent samples from BBr_3 diffusions [22], whereas the red triangles and blue squares correspond to samples that used PECVD BSG as the dopant source.

> "Co-diffusion from doped oxides seems especially suited to n-PERT BJ solar cells."

The formation of the P-doped region can be done either with a P-containing silicon oxide (PSG) deposited (for example) by PECVD or with conventional $POCl_3$ diffusion during/following the thermal drive-in step of the boron. Note that the latter can be done in a single high-temperature process step, similar to the co-annealing after ion implantation. However, during the co-annealing step after ion implantation both B and P are already present in the sample, and the applied temperature budget will always affect both dopants. During co-diffusion, on the other hand, the drive-in of boron from the PECVD BSG can be done first (e.g. at 950°C), followed by a P diffusion at a much lower temperature. As a result, P-doped regions with sheet resistances of 80Ω/sq. and surface concentrations of 10^{20}cm^{-3} can be achieved. These P diffusions have low saturation current densities and can also be contacted using conventional screen-printed Ag pastes. Co-diffusion from doped oxides therefore seems especially suited to n-PERT BJ solar cells: the PECVD BSG layer may be combined with the rear protection layer, thus not adding to the number of processing steps. Later, P and B can be driven in/diffused during the same high-temperature step (replacing the P diffusion), effectively removing the B diffusion as well as the separate BSG etch from the processing sequence. Ultimately, the n-PERT BJ solar cell would feature the same number of processing steps as for a p-PERC solar cell.

This combination of PECVD BSG as the dopant source and a co-diffusion process was applied to n-PERT BJ solar cells on an area of 239cm^2. For the first batches, energy conversion efficiencies of up to 19.8% were achieved, with short-circuit current densities J_{sc} of 38.6mA/cm^2 and open-circuit voltages V_{oc} of 650mV.

Conclusion

By means of two separate quartz furnace diffusions, reference processes were established for bifacial and BJ n-PERT solar cells, yielding efficiencies of up to 20.3% and 20.5% respectively. The n-PERT BJ solar cells were directly compared with p-PERC solar cells, which were fabricated by using the same processing steps and equipment. It was demonstrated that n-PERT BJ solar cells outperform p-PERC solar cells by 0.4% in efficiency after 48 hours of illumination, because of LID of the p-Si. Before LID (or after permanent recovery), p-PERC and n-PERT BJ solar cells achieved similar energy conversion efficiencies.

> "n-PERT BJ solar cells outperform p-PERC solar cells by 0.4% in efficiency after 48 hours of illumination."

The challenge of forming two different full-area highly doped regions can be addressed by employing inherently single-side doping techniques, such as pre-deposition of dopant sources or ion implantation. Both techniques offer specific advantages, in particular with regard to specific cell structures: pre-deposition of dopant sources enables a lean process flow for the fabrication of n-PERT BJ solar cells, while ion implantation is obviously well suited to the fabrication of n-type PERL solar cells. Saturation current densities measured on symmetrical test structures showed that both techniques yield saturation current densities comparable to those obtained in standard quartz furnace diffusions.

Ion implantation and co-annealing have so far been applied to fully screen-printed bifacial n-PERT solar cells, leading to energy conversion efficiencies of up to 20.6%. With PVD Al metallization on the P-doped rear side, efficiencies of up to 20.3% with single screen printing of the AgAl paste, and of up to 20.5% using the dual-print technique on the front side, were achieved. Further investigations into the development of ion-implanted n-PERL solar cells are currently under way. The use of PECVD BSG as a dopant source in combination with a co-diffusion step yielded 19.8% for an n-PERT BJ solar cell.

One should remark that, especially for n-PERT front-junction cells, some technological steps are still less mature than for p-type front-junction cells. In particular, not as much work on optimization has been performed so far on the emitter profile, and screen-print metallization has still to be improved in terms of reduced contact recombination. Given that recent progress continues in these areas, the higher bulk lifetime of n-type material can be expected to yield a higher efficiency benefit in the future.

Outlook

Because an in situ mask can be used to define the processed areas, ion implantation is obviously well suited to the fabrication of n-type PERL solar cells. Implanting phosphorus through a shadow mask, in other words restricting high doping concentrations to the metallized regions, would be beneficial for low specific contact resistances and reduced contact recombination, as well as for reduced Auger and Shockley-Read-Hall surface recombination in the passivated regions. The viability of masked ion implantation has already been demonstrated on p-type solar cells with selective emitters, on ion-implanted IBC cells [19,20], and on n-PERT solar cells with selective boron emitters [17].

Recently, in situ masking of the phosphorus implant was utilized for the fabrication of bifacial n-PERL structures. These structures have so far exhibited efficiencies comparable to those obtained for the n-PERT references. In order to exploit the full efficiency potential of the n-PERL structure, further optimization will be necessary.

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About the Authors

Bianca Lim studied physics at Freie Universität Berlin and did her diploma thesis at Hahn-Meitner-Institut Berlin. She then joined ISFH to pursue a doctorate, focusing on boron-oxygen-related recombination centres in silicon, and was awarded a Ph.D. (Dr. rer. nat.) by the Leibniz University of Hanover in 2011. She is currently a project leader at ISFH, working on simplified processes for local doping and n-type PERT silicon solar cells.

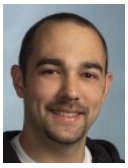
Fabian Kiefer received a diploma degree in physics from the University of Freiburg, Germany, in 2010 for his research on epitaxially grown emitters on crystalline silicon solar cells and on crystalline silicon thin-film solar cells, carried out at the Fraunhofer Institute for Solar Energy Systems (ISE) in Freiburg. In 2010 he joined ISFH, where he is working towards his Ph.D. His research focuses on boron emitters for n-type silicon solar cells.

Nadine Wehmeier has been a Ph.D. student since 2012 at the Institute for Solar Energy Research Hamelin (ISFH), where she works on PECVD doped oxide layers as diffusion sources and co-diffusion processes. She studied physics at the University of Münster and received her M.Sc. in 2011 for her work on silicon multilayer structures for thermoelectric applications.

Till Brendemühl received his diploma degree in engineering physics from the University of Applied Sciences in Emden, Germany. He has been with ISFH since 2005, first working on laser processes and later becoming a project leader with a focus on back-contact high-efficiency solar cells. He is currently working on screen-printed n-PERT solar cells in the solar cell production processes group.

Yevgeniya Larionova studied physics and received her Ph.D. in optics (laser physics) from V.N. Karazin Kharkov National University in Ukraine. From 2002 to 2007 she worked as a research scientist in the Optics Department at Physikalisch-Technische Bundesanstalt (PTB, Braunschweig, Germany). She has been a research scientist at ISFH since 2007.

Frank Heinemeyer studied mineralogy at the Leibniz University of Hanover and received his diploma degree in 1997 on selenization of galvanic-deposited CuIn-layers for $CuInSe_2$ solar cells. He joined ISFH in 2001, working on CIGS solar cells on textile fibres. Since 2007 he has been a project leader in the process technology group, with a focus on the metallization of crystalline silicon solar cells.



Jan Krügener received his diploma and Ph.D. degrees in electrical engineering from the Leibniz University of Hanover, where he is currently an associate researcher in the Institute of Electronic Materials and Devices. His research focuses on the fabrication and characterization of advanced high-efficiency silicon solar cells.

Robby Peibst received his diploma degree in technical physics in 2005 from the Ilmenau University of Technology in Germany. In 2010 he received his Ph.D. from the Leibniz University of Hanover, with a thesis involving germanium-nanocrystal-based memory devices. He joined ISFH in 2010 and has led the emerging c-Si technologies group since 2013. His research focuses on techniques for producing high-efficiency silicon solar cells.

Thorsten Dullweber received his Ph.D. from the University of Stuttgart in 2002. From 2001 to 2009 he worked as a microelectronics project leader at Siemens, Infineon and Qimonda. Since 2009 he has led the ISFH R&D solar cell production processes group, focusing on process and efficiency improvements in industrial-type screen-printed silicon solar cells.

Enquiries

Bianca Lim
Institut für Solarenergieforschung Hameln (ISFH)
D-31860 Emmerthal
Germany

Email: lim@isfh.de
Website: www.isfh.de

R&D of mass-producible PERC cells with average conversion efficiency over 20%

Wei Shan[1,2], **Xiulin Jiang**[1], **Haibin Yu**[1] and **Yong Liu**[1]

[1]Cell R&D Center, JA Solar Holdings Co. Ltd, Yangzhou, China; [2]JA Solar USA, San Jose, California, USA

ABSTRACT

A recent revitalization of the passivated emitter and rear cell (PERC) concept in the silicon PV industry has resulted in solar energy conversion efficiencies of greater than 20% being achieved on p-type solar-grade single-crystalline silicon (mono-Si) wafers during the past two years or so, thanks to technological advance in the use of aluminium oxide for silicon surface passivation. The research efforts carried out at JA Solar in developing an industry version of PERC cells that can be mass produced utilizing the existing conventional back-surface field (BSF) cell manufacturing platform with moderate retrofitting have yielded 20.5% average conversion efficiency, which can be consistently achieved on p-type Si wafers grown by the Czochralski method. Moreover, the experimental results showed that an average conversion efficiency of 20% is achievable when, in combination with JA Solar's proprietary light-trapping technique, the same technological approach is applied to the cells using high-quality polycrystalline silicon (multi-Si) wafers produced by the seeded directional solidification method.

Introduction

The passivated emitter and rear cell (PERC) – or, strictly speaking, passivated emitter and rear locally diffused (PERL) cell – structure has long been considered capable of yielding high energy conversion efficiency in silicon wafer-based single-junction solar cells [1]. If the metal contact on the full area of the back side of a conventional back-surface field (BSF) cell is replaced with a passivation layer or stack and many small localized contacts, the recombination velocity at the back surface can be greatly reduced, resulting in an enhancement of the spectral response in the long-wavelength region of solar irradiance (low photon energies), which leads to an increase in short-circuit current density. The open-circuit voltage is also increased as a result of increased short-circuit current density and decreased diode recombination current at the back contact [2,3]. By using an oxide passivation layer and locally diffused contacts on the back side, together with inverted pyramids structured on the front surface and a double-layered passivation and anti-reflection coating, Zhao and his co-workers [4] in 1998 demonstrated close to 25% conversion efficiency for such a single-junction PERC solar cell using a p-type float-zone Si wafer.

The advantages of the PERC concept are that, in principle, it does not impose on the wafers the same necessary requirement of high quality as for interdigitated back contact (IBC) and heterojunction with intrinsic thin layer (HIT) cells (see, for example, Maruyama et al. [5] and Mulligan et al. [6], and references therein); more importantly, it can be structured on p-type wafers, from which the vast majority of solar cells have been made in the past, and still are today. However, for many years the industrial adoption of the PERC structure for the mass production of solar cells using silicon wafers has been very limited, primarily owing to the complexity of the use of thermal oxidation to obtain satisfactory passivation quality. Additionally, there are concerns about the creation of local contacts through localized diffusion without significantly degrading the quality of the wafers, as well as the manufacturing cost associated with the cell fabrication process.

> "The PERC concept does not impose on the wafers the same necessary requirement of high quality as for IBC and HIT cells."

On the other hand, aluminium oxide (Al_2O_3 in non-stoichiometric form) for silicon surface passivation was proposed by Jaeger & Hezel [7] nearly three decades ago. Since the demand for lower-cost but higher-efficiency cells has increased in recent years, and the price of silicon wafers has steadily decreased, the effectiveness of Al_2O_3 passivation has been revisited and more extensively studied. A number of research groups have been able to experimentally demonstrate that a thin layer of Al_2O_3 or a dielectric stack of Al_2O_3/SiN_x is very effective and efficient in producing high-quality passivation, especially on p-type silicon surfaces, without the need to subject the Si wafers to a high-temperature thermal oxidation process followed by a forming gas anneal for surface passivation [8,9]. The understanding of the fundamental physics involved in the passivation mechanism of Al_2O_3 on Si surfaces has revitalized PERC R&D activities in the silicon PV community. During the last few years, as innovative high-throughput Al_2O_3 deposition tools specifically designed for PV applications, based on various deposition methods such as spatial atomic layer deposition (ALD) and plasma enhanced chemical vapour deposition (PECVD), have become available and more adaptive to the PV industry, the approach of using Al_2O_3 film for PERC cell back-side passivation has gained considerable momentum (see, for example, Kessels & Putkonen [10] and references therein). All of this has resulted in an accelerated transition of the PERC concept from research laboratory prototypes to industrial solutions for high-performance solar cells.

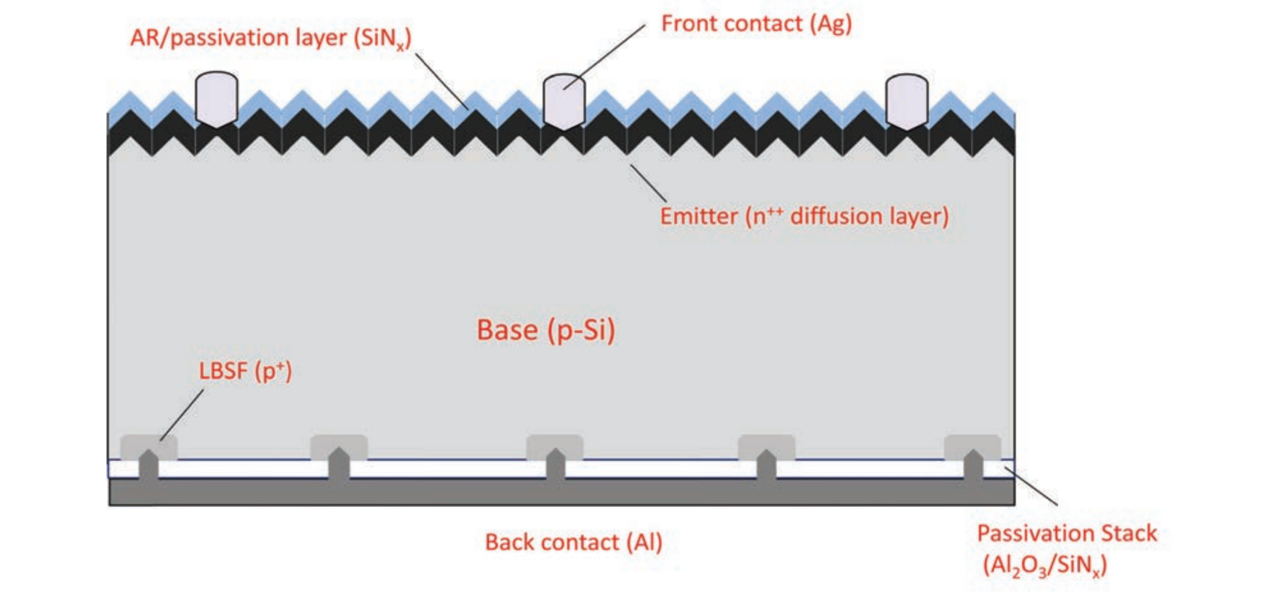


Figure 1. Schematic illustration of the PERC cell structure (not to scale).

In this paper it is shown that, by incorporating a few extra process steps, which include the deposition of an Al_2O_3/SiN_x stack on the back side of Si wafers and the formation of a localized contact pattern by pulsed laser opening, into the mainstream conventional BSF cell manufacturing flow, an average conversion efficiency above 20% for PERC cells can be readily achieved using commercially available p-type mono-Si wafers. In addition, JA Solar's very recent experimental results have demonstrated that, with the implementation of the same technical approach in combination with an advanced light-trapping scheme, a 20% average conversion efficiency can be obtained for PERC cells using casted polycrystalline Si wafers.

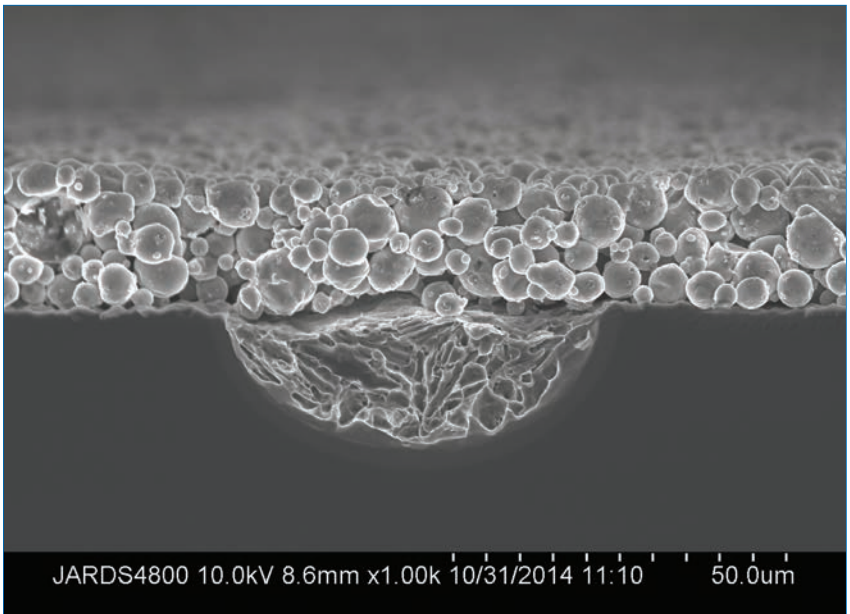


Figure 2. Cross-sectional SEM image of a local BSF formation.

Experimental details

The starting material for PERC cell development was solar-grade silicon wafers, sliced from boron-doped p-type single-crystalline silicon ingots grown by the Czochralski method. The wafers were of a typical industrial size, nominally 156mm × 156mm, with a thickness of 180±10μm and a bulk resistivity in the general range of 1.0–3.0Ω-cm.

A schematic illustration of the device structure of a PERC cell is shown in Fig. 1. The cell structure is basically the same as that of a conventional full BSF cell, apart from the back side. The front side consists of a homogeneous emitter (a heavily doped n^+ layer) formed by doping the silicon with phosphorus through thermal diffusion after the surface is textured by anisotropic etching. On top of the emitter, a thin layer of SiN_x is deposited using the PECVD method to provide anti-reflection and passivation for the front surface; a number of metal (Ag) fingers that make direct contact with the emitter are also deposited. The back side of the cell is covered by a dielectric stack of Al_2O_3/SiN_x, with a fairly thick aluminium layer on top as the current conduction electrode. The dielectric stack is formed by first depositing a very thin (~5–25nm) layer of Al_2O_3 on the bare Si surface using either the ALD or the PECVD method; this is followed by a relatively thick (≥100nm) SiN_x layer deposition using PECVD.

The Al contact to the Si wafer is made through a group of patterned openings on the Al_2O_3/SiN_x stack using a pulsed laser. The predetermined opening pattern dictates that the contacts will be made only through the openings in a controlled manner, and forces the formation of heavily doped p^+ regions to be localized underneath the openings where the Al contacts the Si, thereby creating the so-called local back-surface field (LBSF). In this way, the number of contacts and the total area of metal contacts, as well as the dissolution of Si in Al during metallization (making electrical contacts), can be finely controlled.

The cross-sectional SEM image in Fig. 2 shows the details of such a local contact on the back side of a PERC cell. The thick Al layer was screen printed onto the back surface of the Si. There is no direct contact between the top Al layer and the underlying Si substrate along the interface, because they are separated by an Al_2O_3/SiN_x

stacking layer (too thin to be visible in the image), apart from a bowl-shaped feature protruding into the Si bulk at the location where there is an opening in the dielectric layer. That feature is a typical example of an LBSF formed by a process of Al alloying with Si during a rapid thermal treatment referred to as a 'co-firing process' [11], resulting in low resistive ohmic contact between Al and Si. The co-firing process also brings the Ag fingers that are screen printed on the front surface into intimate contact with the n^+ emitter by punching through the SiN_x layer.

Results and discussion

Both the ALD and PECVD methods were used to deposit aluminium oxide thin film onto the silicon wafer surface. The experimental results showed that the recombination velocity at the back surface can be controlled to well below 100cm/s, with the implied open-circuit voltage (iV_{oc}) ranging from around 680 to 690mV before metallization. Considering the quality of the wafers used in this work, as well as the fact that the size of the textured surface area was much larger than the actual wafer, these numbers are in good agreement with the reported values in the literature [12] (and see, for example, Werner et al. [13] and references therein).

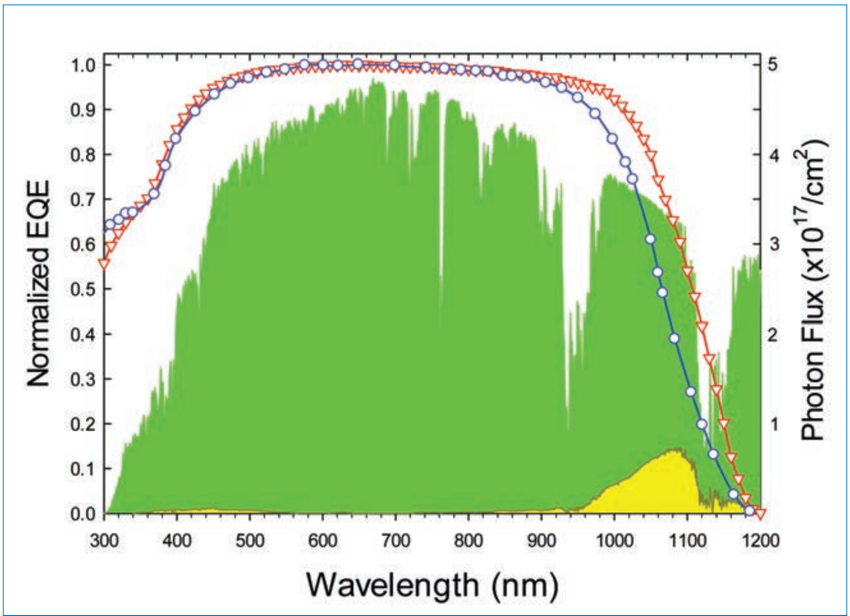


Figure 3. Measured EQE of a 20.25% PERC cell (red triangles/line) compared with that of a 19.1% conventional full BSF cell (blue circles/line). The shaded green area is the photon flux of AM1.5G solar irradiance, and the yellow area represents the net difference between the integrated photon fluxes governed by the EQE of the respective PERC and conventional cells.

Mono-Si PERC cells

Given that the surface recombination velocity at a PERC cell's back surface has been significantly reduced, and that the diode recombination current has been significantly decreased by shrinking the metal contact area from almost 100% of conventional full BSF down to a mere few per cent of localized BSF on the back side, it becomes straightforward to achieve >20% conversion efficiency using commercially available mono-Si wafers, as compared with the baseline of >19% efficiency mono-Si cells with full BSF.

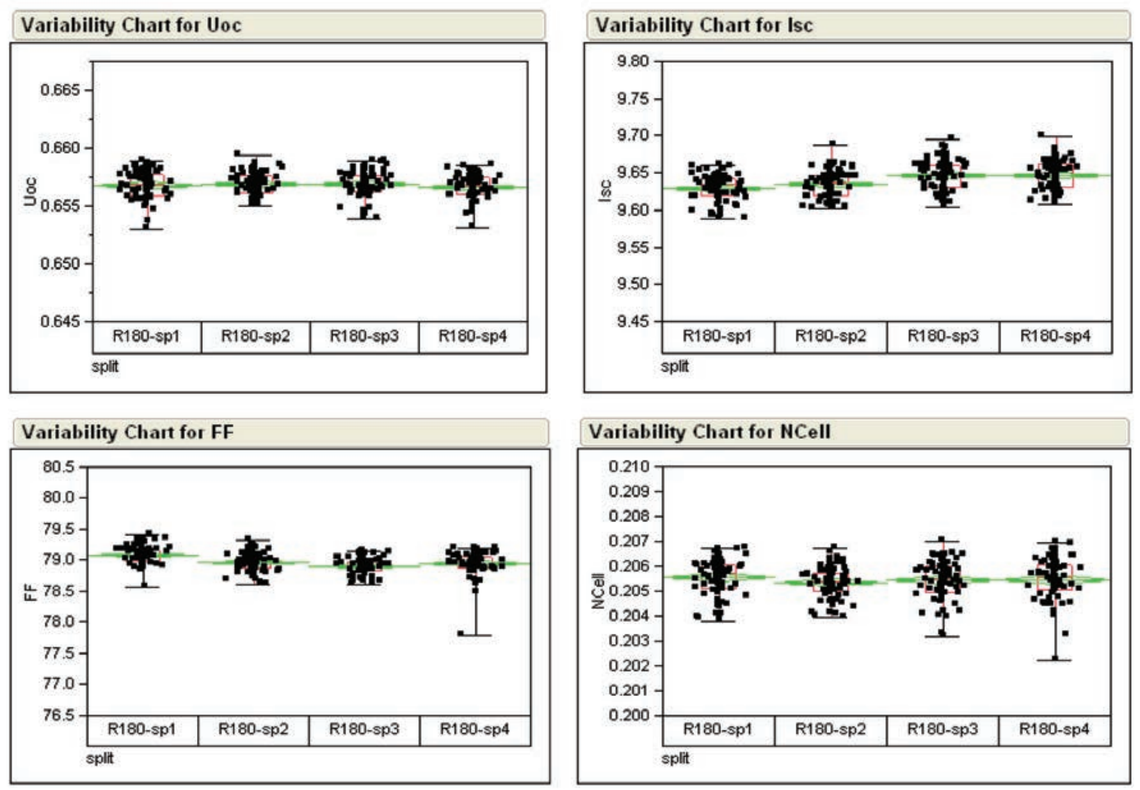


Figure 4. Variations of key cell performance parameters (V_{oc}, I_{sc}, *FF* and η, respectively) from one experimental run. The cells were split equally into four groups and processed under different conditions.

"The much-enhanced spectral response exhibited by the PERC cell in the long-wavelength region in particular is the key factor in boosting cell conversion efficiency."

Fig. 3 shows the measured normalized external quantum efficiency (EQE) of a PERC cell with 20.25% conversion efficiency [14], together with the EQE curve for a full BSF cell with 19.1% efficiency. The green area in the figure is the photon flux of standard solar irradiance (air mass 1.5 global – AM1.5G) as a function of wavelength in the spectral range of the EQE measurements. As can be seen from Fig. 3, while there is not much difference in the EQE between two samples in the short-wavelength region (because the device structures at the front side of both types of cell are the same), the difference in the long-wavelength range is very prominent. The much-enhanced spectral response exhibited by the PERC cell in the long-wavelength region in particular is the key factor in boosting cell conversion efficiency, because more carriers generated by the photons in the spectral range are available for collection as a result of the significant reduction in the recombination of photogenerated carriers in the vicinity of the back surface passivated by Al_2O_3 and in the metal contact areas. The net difference in the photo flux (~9.3×10^{16}/cm^2) corresponding to the greater number of carriers flowing out of the cell in short-circuit connection under one-sun conditions (AM1.5G) is illustrated by the yellow area in the figure. This enhancement in quantum efficiency results in not only a ~1.5mA/cm^2 increase in short-circuit current density (J_{sc}), but also a >10.0mV higher voltage for all the carriers out of the PERC cell. This in turn leads to a gain in efficiency of more than 1% abs. for PERC cells over conventional full BSF cells.

To provide a true picture of industrial R&D results, a set of cell results from one of many experimental runs is shown in Fig. 4: key cell performance parameters – open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor (*FF*) and conversion efficiency (η) – are displayed in their respective variability charts. In this experimental run, a batch of 400 full-square mono-Si wafers was split equally into four groups and processed under different conditions at certain steps of the cell fabrication procedure. It can be seen from the figure that the conversion efficiency averaged over all the cells in every single group is above 20.5%. Note that, despite each split in this experiment being subjected to slightly different process conditions, they all yield approximately the same conversion efficiency, indicating that the process window for PERC cell manufacturing is fairly large.

Multi-Si PERC cells

Multi-Si wafers produced by the directional casting method have traditionally been regarded as only suitable for making solar cells at a low cost but with mediocre performance because of their relatively low crystal quality. In the past few years, high-quality multi-Si wafers with uniform grain size and low density of dislocations have become commercially available as a result of the recently developed seeded directional solidification method [15–17]. The current consensus in the industry is that the conversion efficiency of solar cells made from these high-quality multi-Si wafers is on average ~0.3–0.5% higher than that for cells using regular multi-Si wafers. For example, in mass production at JA Solar the average conversion efficiency of the cells using such wafers is currently ~18.0±0.1%.

With the 18% efficiency being set as a baseline, the application of the same PERC technical approach as used for mono-Si cells enabled >19.0% average conversion efficiency to be realized in early 2014 from the cells using high-quality multi-Si wafers. In order to further improve cell performance, an advanced proprietary light-trapping approach was developed to overcome the problem of high reflection inherently associated with the acidic textured surface of multi-Si wafers. The average efficiency has gradually been improved since then, with greater than 20% having recently been achieved [18]. Fig. 5 shows a typical *I–V* characteristic taken from one sample out of a batch of such multi-Si PERC cells; its conversion efficiency is 20.1%. The inset in the figure indicates the variation of conversion efficiency from approximately 1600 cells divided equally into four groups. Note that the relatively wide efficiency distribution observed from the finished cells is very typical for multi-Si cells, even with high-quality wafers being used, primarily because of the large variation in crystal quality due to its polycrystalline nature. Nevertheless, the achievement of an average conversion efficiency greater than 20% is quite an accomplishment for the silicon PV industry.

The additional 1% abs. efficiency improvement can be chiefly attributed to the incorporation of a proprietary light-trapping scheme into the multi-Si PERC cell fabrication process; this scheme significantly reduces the reflection from the multi-Si cell surface. Fig. 6 shows the plots of the EQE and reflection curves for the PERC cell, along with those for an 18.0% conventional multi-Si cell. It can be observed that the overall effect of combining the light-trapping scheme with the PERC structure, aided by the presence of a dielectric stack covered by a thick layer of Al on the cell back side, is a vast improvement in the cross-band spectral response, leading to the considerable boost in both I_{sc} and V_{oc} for the cells.

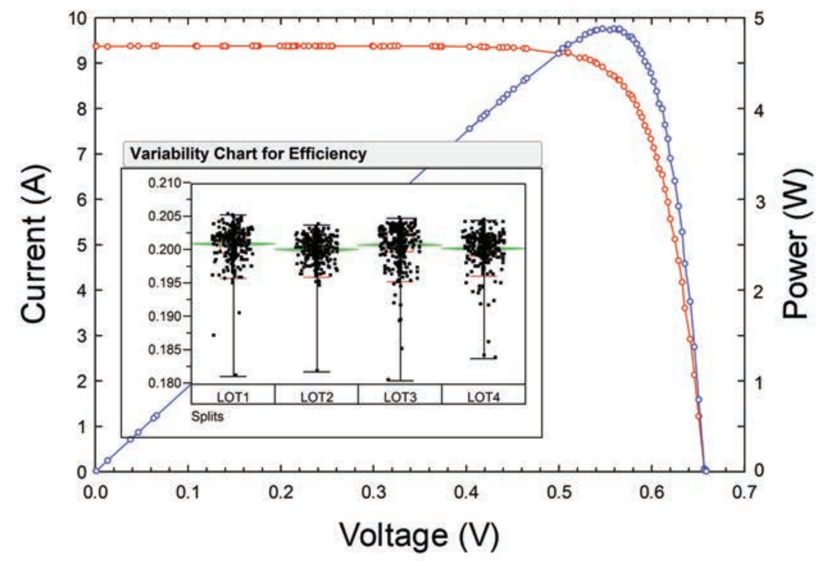


Figure 5. *I–V* characteristic of a multi-Si PERC cell with 20.1% conversion efficiency. The inset shows the distribution of cell conversion efficiency in ~1600 cells divided equally into four groups.

> "The additional 1% abs. efficiency improvement can be chiefly attributed to the incorporation of a proprietary light-trapping scheme."

Concluding remarks

To date, well over 100,000 cells have been fabricated in many experimental runs in order to validate cell design and the corresponding manufacturing process, to simulate mass-production conditions, to verify settings for equipment and tools that are to be retrofitted into the current mass-production manufacturing platform, and, most importantly, to continue to improve the performance and test the reliability of the cells. The industrial version of screen-printed PERC cells reported in this work has been demonstrated to be clearly superior to conventional full BSF cells in terms of cell performance of both single-crystalline (mono-) and polycrystalline (multi-) Si wafers, with greater than 20.5% and 20.0% average conversion efficiencies, respectively, being realized.

The PERC cell process with the addition of a dielectric Al_2O_3 passivation layer or Al_2O_3/SiN_x stack on the back side of a Si cell, and a structuring of localized contacts (LBSF) through laser opening, does not require p-type wafers of the highest quality in order to achieve more than a 1% gain in efficiency. Furthermore, the process can be implemented on a conventional Si solar cell manufacturing platform without significantly changing the cell process flow. It is important to note that, especially when concerns about the costs of manufacturing wafer-based Si cells need to be addressed, the cell process window is opened up considerably by obtaining an excellent passivation effect from Al_2O_3 without subjecting the Si wafers to high-temperature thermal oxidization to achieve the required passivation effect. The approach of using short-pulse laser ablation to form contact openings is fully compatible with the screen-printing-based cell manufacturing platform. Of course, the choice of the right deposition method and equipment, including laser ablation tools, and their coherent integration into existing cell manufacturing lines, as well as the set-up of optimized process parameters, are all of vital importance in making PERC cells mass producible. Fortunately, the success of this has been made much easier by the recent rapid progress in the development and commercialization of high-throughput Al_2O_3 deposition equipment and pulsed laser processing tools.

> "The implementation of the PERC device structure into mainstream p-type Si solar cells is expected to be a prevailing technological trend in the next few years."

Finally, it has to be pointed out that more than 90% of the PV modules produced today worldwide are based on crystalline silicon wafer technologies. Approximately 35–40% of these modules are based on single-crystal silicon grown by the Czochralski pulling process, and 60–65% are based on polycrystalline ingots cast in crucibles by directional solidification. Among these modules, over 95% are assembled by p-type wafer-based Si cells and dominate the global production of solar electricity. Therefore, as the performance of PERC cells is continually being improved, the

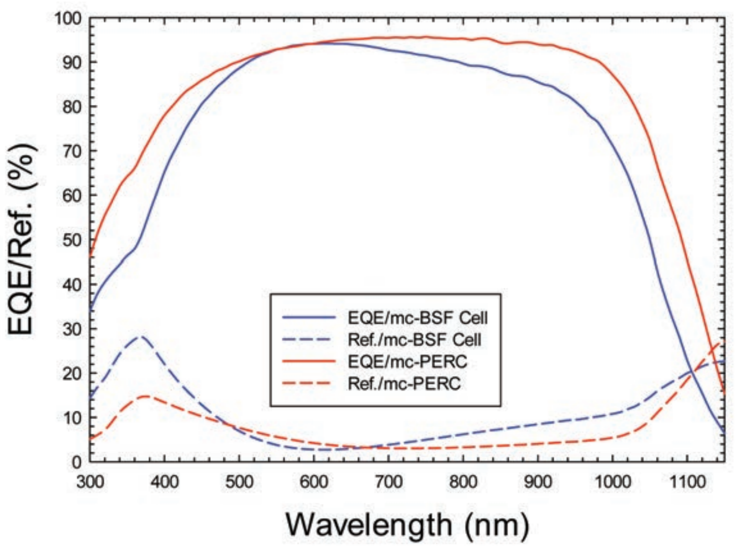


Figure 6. Comparison of the EQE and reflection of an 18.0% conventional multi-Si cell (mc-BSF cell, blue lines) and a 20.1% multi-Si PERC cell (mc-PERC, red lines).

implementation of the PERC device structure into mainstream p-type Si solar cells is expected to be a prevailing technological trend in the next few years.

Acknowledgements

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About the Authors

Dr. Wei Shan has been with JA Solar since 2008 and is currently the chief scientist and head of R&D. With more than 30 years' experience in R&D in a wide variety of semiconductor material systems and devices, he has published over 150 peer-reviewed journal articles and prestigious conference papers, as well as six book chapters.

Xiulin Jiang studied materials physics at the University of Science and Technology of Central China. He has been working in the Research and Development Center at JA Solar since 2007.

Haibin Yu studied control technology and instrumentation at the University of Science and Technology of Qingdao, China, where he received his bachelor diploma in 2005 and completed his master's in 2010. He has been working at JA Solar's Research and Development Center since joining the company in 2008.

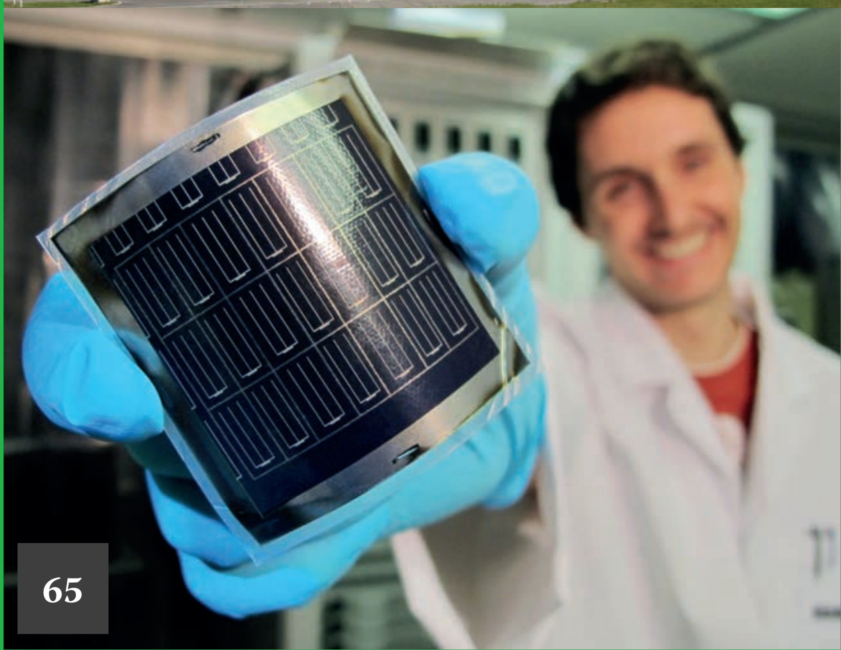
Yong Liu has been with JA Solar since 2008 and is the chief technology officer. He has many years of experience in the semiconductor IC chips manufacturing sector and expertise in leading technology development. He also currently serves as JA Solar's chief operations officer.

Enquiries

Wei Shan
Cell R&D Center
JA Solar Holdings Co. Ltd
1 Jianhua Road
Yangzhou
225000 Jiangsu
China

Tel: +86 (514) 8554 8278
Email: weishan@jasolar.com
Website: www.jasolar.com

Thin Film



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CIGS thin-film solar cells – Breakthroughs for further efficiency improvements

Stephan Buecheler, Fabian Pianezzi, Patrick Reinhard, Enrico Avancini, Lukas Kranz, Fan Fu & Ayodhya N. Tiwari, Laboratory for Thin Films and Photovoltaics, Empa – Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland

First Solar restoring idled production lines in Malaysia and adding two lines in Ohio

First Solar has said it will restore idled production lines at its main production plant in Malaysia, bringing back 360MW of capacity. The company also said it would add two new lines at its facility in Ohio, providing a further 178MW of nameplate capacity in 2015.

The capacity restoration and two new lines are to meet First Solar PV project construction needs and third-party module sales demand in 2015. The changes to the US Investment Tax Credit as well as a number of international markets that are building demand were also cited for need for extra capacity.

First Solar also said it was delaying the major ramp and introduction of its Series 4 CdTe thin-film modules until 2015 due to customer orders specifically for its Series 3 modules.

However, its Series 4 modules were said have reached efficiencies of 15.9%, compared to current average production efficiencies of 14.2% and expected 14.4% efficiencies expected in the fourth quarter. First Solar had previously guided that each CdTe line would reach an average line run rate of 89MW per annum by the end of 2014.

Source: First Solar

First Solar is restoring idled production lines at its Malaysia plant.

Thin-film company news

Manz close to first 'CIGS fab' deal as record revenue revealed

High-tech manufacturing equipment firm, Manz AG, reported record revenue for the first nine months of 2014, driven by its Flat Panel Display segment, which generated €179.9 million (US$224.2 million) from the total revenue of €250.9 million.

Revenue generated from its Solar segment remained at very low levels but the company noted improving conditions. Solar segment sales were €9.3 million in the first nine months of 2014, compared to €7.5 million in the prior year period.

Although regular payments of €4.5 million from Wurth in respect to the transfer of its CIGS thin-film technology ended, management noted that a potential sale of its first turnkey 'CIGS fab' in the "short term" was possible, offering additional revenue upside to its Solar segment in the fourth quarter of 2014.

First Solar drops full-year revenue guidance on US project delays

First Solar reported third quarter net sales of US$889 million, an increase of US$345 million from the second quarter of 2014. However, project delays would result in full-year revenue guidance lowered by US$100 million to a range of US$3.6 billion to US$3.9 billion, it said.

The sequential increase in net sales resulted primarily from increased revenue recognition on the Desert Sunlight project, according to First Solar. The company reported a gross margin of 21.3%, up from previous guidance and up 4.3 percent points from the previous quarter. First Solar said that operating income was US$81.9 million, down slightly from US$83.8 million in the prior quarter.

Source: Manz

Manz anticipates the sale of its first turnkey CIGS fab.

Thin-film OPV firm Heliatek raises €18 million to ramp production

Dresden-based OPV thin-film start-up, Heliatek GmbH, has raised €18 million in a 'Series C' investment round that included German entrepreneur, Stefan Quandt.

Heliatek said that the funds would support market entry and operations into 2016. The firm is planning to launch products for BIPV and automotive sectors. Stefan Quandt is part of the family that owns a majority share in German car giant BMW.

Thin-film projects

South Africa's largest thin-film PV power plant complete

De Aar 3, an 85MW solar project said to be the largest solar farm in South Africa using thin-film modules, has been completed. The project was undertaken by Solar Capital De Aar, a joint venture between Italian renewable energy developer, Moncada Energy Group, and solar funder, Solar Capital Group.

De Aar 3 uses over 200,000 amorphous silicon thin-film modules manufactured by a Moncada subsidiary in Italy. The plant's funding was administrated by Solar Capital's South Africa subsidiary, Phelan Energy Group, and the project was built by Moncada subsidiary, Costruzioni Moncada South Africa.

First Solar and Belectric UK collaboration closing in on 80MW of large-scale solar

First Solar and Belectric have started construction of one of the UK's largest solar farms, a 46MW project in Oxfordshire that will bring large-scale PV capacity deployed by the pair in the UK up to 80MW when completed.

The facility will consist of more than 483,000 of First Solar's thin-film modules, with Belectric handling the construction and balance of systems requirements for the project. The Oxfordshire solar farm is the fourth collaboration between the companies following the formation of a joint venture in 2013. The companies' four UK solar projects to date now total 80MW of capacity. The first three of those projects were all connected in June.

First Solar and Belectric's collaboration in the UK is nearing 80MW-worth of projects.

Source: argylenews.

Japanese golf course to become 15MW solar park

Construction has begun on a 15MW solar park on a former golf course in Japan. Housing developer, Takara Leben, which owns the former golf course, teamed up with industrial engineering corporation, Hitachi Zosen, which will deliver engineering, procurement and construction services, with thin-film modules to be supplied by Solar Frontier.

Land constraints have proved to be an issue for Japanese solar developers in the past with floating arrays and reclaimed land proposed for solar installs. The former golf course is in Nakagawa, Tochigi Prefecture, Japan and will sell power generated to the grid.

News

Source: Hanergy.

Hanergy is to press ahead with its new 300MW CIGS module fab in China.

Hanergy news

Hanergy fires starting gun on 5.25GW CIGS expansion

Hanergy has confirmed details of a new 300MW CIGS thin-film factory in Hunan Province. The fab forms part of the company's longer term 5.25GW capacity expansion plans for its CIGS products revealed in November 2013.

In a statement to the Hong Kong stock exchange, the company said the plant was "a milestone in the Group's capability in producing thin film photovoltaic modules on its own", adding that this would "help the Group in diversifying its revenue and customer base, but will also open up the whole industry chain, thus reducing the overall cost".

Tool maker Beijing Jing Cheng, a Hanergy subsidiary, has been selected to provide the productions lines for the facility in Changde City, Hunan Province.

The factories will be built by the Changde Government which will then lease the sites at "at a concessionary rate" to Beijing Jing Cheng. Construction is expected to be completed in June 2016.

Hanergy completes name change

The board of Hanergy has approved a change of name for the company. After having already received shareholder approval for the move in August, Hanergy will now change its name from Hanergy Solar Group Limited to "Hanergy Thin Film Power Group Limited".

A statement to the Hong Kong Stock Exchange said the change of name would have no material impact on the day to day running of the company.

Hanergy completes first phase of BIPV install at Beijing headquarters

Thin-film manufacturer, Hanergy, has completed the first phase of a BIPV install at its headquarters in Beijing, covering the building's exterior almost entirely with 600kW of thin-film PV.

By integrating its own technology onto the walls of its main offices, Hanergy now meets 20% of the building's electricity demand, but by the end of the project, the BIPV technology will provide 100% of the building's energy needs.

The second phase of the project will incorporate thin-film solar technology into curtain-walls, skywalks, flexible roof installations, a carport, and have a 3MW total installed capacity, all the while maintaining the building's original architecture.

The completed project will not only save the company from the cost of an electricity bill, but it will earn RMB0.42/kWh (US$0.069/kWh) in distributed power subsidies.

Hanergy to set up solar R&D centre in Silicon Valley

Hanergy Thin Film Power is setting up a product development business with a research centre to be established in Silicon Valley. The Chinese manufacturer and project developer will establish seven new units in total as part of a new Product Development Group, according to a statement made to the Hong Kong Stock Exchange.

The organisation will be led by Hanergy Thin Film Power chairman Li Hejun.

Technology advances

New Solar Frontier fab to trim one third off CIGS cost

Japanese thin-film manufacturer Solar Frontier has said its next-generation fab will trim a third off the cost of producing its CIGS modules.

In a statement the company said the 150MW Tohoku plant would be complete by March next year, offering a number of technological advances over its existing 900MW Kunitomi plant.

Dyesol mulling pilot line phases for perovskite-based thin-film products

Thin-film OPV firm, Dyesol has said it was undertaking the planning phases of commercialising its solid-state DSC technology using perovskite-based thin-films.

The company said that both prototype and pilot line phases of planning were expected to be concluded in 2016 and 2017, respectively. Mass production was said to be by 2018.

ZSW sets 21.7% CIGS cell record

Researchers at the Centre for Solar Energy and Hydrogen Research (ZSW) in Stuttgart have achieved a 21.7% conversion rate in a CIGS thin-film cell, a new record.

The new efficiency rate, confirmed by the Fraunhofer Institute for Solar Energy Systems, beats the previous record of 21% set earlier this year by Swedish researchers.

Michael Powalla, head of ZSW's PV division, said the advance extended the efficiency lead of CIGS over multicystalline PV cells by 1.3%, offering the prospects of extending the market reach of CIGS technology.

CIGS thin-film solar cells – Breakthroughs for further efficiency improvements

Stephan Buecheler, **Fabian Pianezzi**, **Patrick Reinhard**, **Enrico Avancini**, **Lukas Kranz**, **Fan Fu** & **Ayodhya N. Tiwari**, Laboratory for Thin Films and Photovoltaics, Empa – Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland

ABSTRACT
During the past two years remarkable performance improvements have been reported for polycrystalline $Cu(In,Ga)Se_2$ (CIGS), CdTe and perovskite thin-film solar cells. In this paper the key breakthroughs in CIGS thin-film technology are reviewed and the scope for further performance improvements by analysing the still-remaining electrical and optical losses in record-efficiency CIGS solar cells is discussed. On the basis of this analysis it is believed that conversion efficiencies up to 25% are achievable with CIGS solar cells in the mid term. Furthermore, the potential for the concept of polycrystalline multi-junction solar cells to push efficiencies even further, towards 30%, is discussed. Finally, a short review of the CIGS market and an outlook from an industrial perspective are presented.

Introduction

Recent progress in the field of thin-film PV demonstrates the potential for the production of low-cost, highly efficient and durable solar modules in the near future. In particular, an outstanding performance of close to 22% energy conversion efficiency has been achieved at a research level by technologies based on $Cu(In,Ga)Se_2$ (CIGS), exceeding the highest reported efficiency of 20.4% of the current market-dominating polycrystalline silicon (px-Si) wafer-based technologies.

The minimum layer thickness of the materials required to efficiently absorb sunlight is 2–3µm, which is about one hundredth of what is necessary for px-Si wafers. This carries obvious advantages in terms of the amount of material needed, and the large-area manufacturing processes enable the construction of thin-film solar modules with shorter energy payback times. Furthermore, thin-film technology allows the creation of flexible solar cells through deposition on polymer films or metal foils. Flexibility combined with light weight and high efficiency is a key advantage in applications such as building-integrated PV (BIPV) and rooftop installations; moreover, these characteristics have a significant impact on reducing overall system cost.

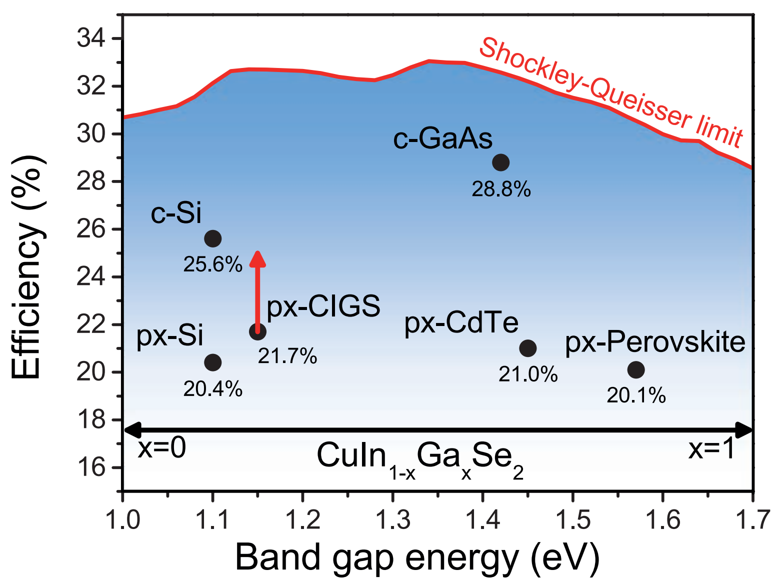


Figure 1. Shockley-Queisser limit (accounting for radiative recombination) for single-junction solar cells under an AM1.5G spectrum. Also shown are selected record efficiencies for different monocrystalline (c-) and polycrystalline (px-) PV technologies.

> "The optimal band gap of an absorber layer for the most efficient conversion of sunlight into electricity is between 1.1 and 1.5eV, with a corresponding maximum theoretical efficiency close to 33%."

Polycrystalline CIGS is a stable p-type semiconductor material that can be used as the absorber layer in a thin-film solar cell. Its band gap can be continuously tuned from 1.0 to 1.7eV by changing the ratio of In to Ga. This covers the ideal band-gap range for converting solar energy to electricity if compared with the Shockley-Queisser limit, which defines the theoretical maximum achievable conversion efficiency (Fig. 1). On the basis of those calculations, the optimal band gap of an absorber layer for the most efficient conversion of sunlight into electricity is in fact between 1.1 and 1.5eV, with a corresponding maximum theoretical efficiency close to 33%. For CIGS solar cells, the highest efficiencies have so far been achieved with an average energy band gap of 1.15–1.2eV.

There is still a large gap, however, between the Shockley-Queisser limit and the actual achieved values for current record 21.7%-efficiency CIGS solar cells. An argument that further progress can still be made to increase efficiencies by reducing the optical and electronic losses is discussed in this paper. It is now believed that efficiencies up to 25% are within reach in the mid term. Some aspects of CIGS development that have led to the current solar cell configuration and efficiency are presented here, and the origin of the remaining losses in record-efficiency devices is discussed.

Finally, the path towards multiple-junction polycrystalline thin-film solar cells in order to achieve even higher efficiencies approaching 30% is presented. Some aspects of production costs and industrial players are discussed, highlighting the unique advantages of this technology that should allow the cost of PV modules to be brought down even further, while opening the door to innovative applications and new markets.

A brief history of CIGS solar cell processing

From the appearance of the first solar cells with copper indium selenide (CIS) single crystals combined with evaporated CdS in 1974 [1] to the achievement of the recent record efficiency of 21.7% [2], many material combinations and growth methods have been tested, leading up to the current CIGS stack configuration (shown as an inset in Fig. 3). The typical substrate of the record-efficiency solar cells is soda-lime glass, but recently similar efficiencies have been reported on flexible polyimide substrate, in spite of the limitation of the low deposition temperature (<500°C) imposed by the plastic substrate. A sputtered Mo layer is used as a back contact, followed by a CIGS absorber grown by evaporation of individual elements or by sputtering followed by selenization. The pn junction is formed by the deposition of a so-called 'buffer layer', which is usually of n-type CdS deposited in a chemical bath, but alternative buffer layers, such as Zn(O,S), can also be used. The device is finished by a transparent conductive oxide (TCO), such as ZnO doped with Al or ITO, as well as a metal grid for better current collection.

Some of the advances have had a significant impact on the progress of technology. The first innovation was the introduction of a thin (< 100nm) n-doped CdS buffer layer [3], which allowed the formation of a good-quality p-n junction with limited interface recombination between the CIGS absorber and the next layer, along with reduced optical losses due to absorption in the CdS layer.

A second major leap forward was realized when the role that Na plays in the CIGS electronic properties was reported [4]. Na is naturally present in the soda-lime glass substrate material and diffuses into the CIGS layer during growth at an elevated temperature, improving the electronic quality of the CIGS, which significantly enhances the solar cell efficiency. Furthermore, the partial replacement of In by Ga to increase the band gap of the absorber has led to a further efficiency improvement [5].

From a CIGS growth perspective, the shift from the co-evaporation process introduced by Boeing (evaporation from separate elemental sources) [6] to the so-called 'three-stage method' by NREL [7] paved the way for all further efforts towards achieving high efficiencies, allowing the growth of CIGS layers with enhanced crystalline quality, grain size and electronic properties; those concepts led to a 19.9% cell efficiency in 2007 [8]. Fig. 2 shows the subsequent improvements in cell efficiency, comparing high- and low-temperature deposition processes, along with the progress of the highest-reported mini-module efficiency on plastic substrate. After 2007, the efficiency gap with px-Si solar cells became even less: incremental improvements in cell efficiency reached 20.3% [11] in 2011, mainly driven by optimization of the deposition methods, without any actual breakthrough in terms of material composition and deposition techniques.

A new boost in efficiency improvement, however, was recently triggered by Empa with the introduction of a novel processing step based on a post-deposition treatment (PDT) of the CIGS absorber layer with potassium fluoride (KF) [12,13].

In the process of depositing CIGS layers onto alkali-free substrates, alternative methods had to be developed in order to add the alkali, mainly Na, to take advantage of its beneficial effect on performance. In 2004 the concept of a PDT for doping CIGS layers with alkaline was developed at ETH Zürich (the research group relocated to Empa in 2009) [14]: NaF is evaporated onto the CIGS absorber at a temperature of around 350°C after growth has finished, allowing diffusion of Na into the layer and yielding similar effects on the absorber electronic properties to those when diffusing from the glass substrate. Most notably, this immediately allowed an improvement in record efficiencies of cells grown on flexible plastic films [15].

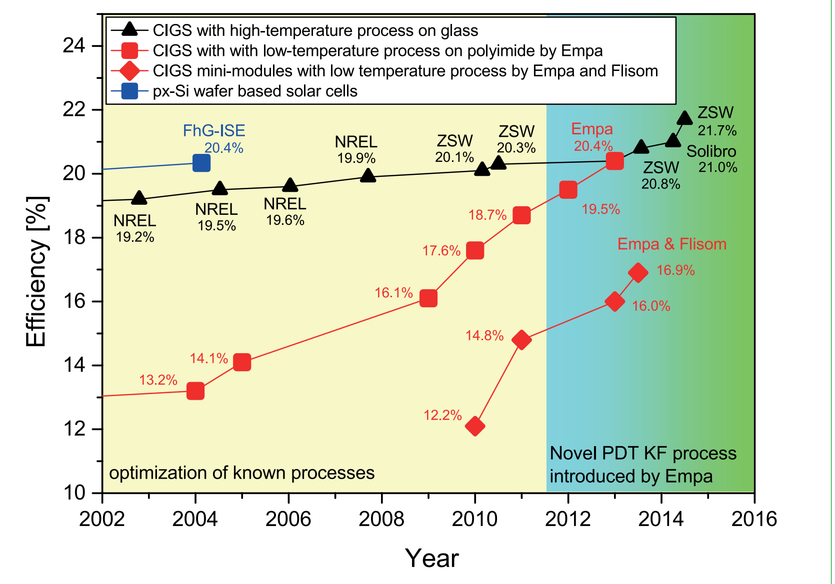


Figure 2. Efficiencies of CIGS solar cells processed by co-evaporation methods on glass substrates at high temperatures and on flexible polyimide films at low temperatures. Efficiencies are also shown for mini-modules processed by low-temperature co-evaporation (but not for those processed at high temperatures). With such high-temperature processes, Solibro has achieved a designated area efficiency of 18.7% for a mini-module [9]. The values for CIGS solar cells using a high-temperature process, as well as the values for px-Si, are taken from NREL [10].

"The introduction of potassium after the absorber growth has led to an efficiency of 20.4% on a flexible polyimide substrate."

For a long time, Na was believed to be the most effective alkali element, which is a valid argument when it is present before or during CIGS growth. However, the introduction of potassium after the absorber growth has led to an efficiency of 20.4% on a flexible polyimide substrate and has proved advantageous in improving the quality of the interface between the CIGS absorber and the CdS buffer layer. Not long after that was announced, a new record of 20.8% on glass using a process based on KF PDT was reported [16]; more recently, further outstanding improvements in efficiency of up to 21.0% at Solibro [17] and 21.7% at ZSW [2] have been achieved using KF PDT.

Conventionally, these CIGS absorbers are grown by the co-evaporation of Cu, In, Ga and Se following a three-stage or multi-stage process. However, sputtering of Cu, In and Ga metallic precursors, followed by selenization and sulphurization processes, has also yielded a cell efficiency above 20% [18] using a Cd-free buffer layer.

Overall, it is of fundamental importance not only to control the actual compositions of the CIGS and the other layers in a solar device, but also to adapt suitable techniques to grow and combine the different layers without any adverse effects on the properties of the previous and subsequent layers. Aspects such as compositional grading throughout the absorber layer, the amount and nature of crystal defects, or the elemental inter-diffusion at interfaces all have consequences for the final photovoltaic properties of the solar cells; understanding their interdependencies is essential for the processing of high-efficiency solar cells.

Potential for further performance improvement of up to 25% efficiency

As previously mentioned there exists a fundamental physical limit to the performance of single-junction solar cells (Shockley-Queisser limit) which assumes that, in equilibrium, the generation of charge carriers has to be balanced by an equal amount of recombination, and no other losses are present [19]. However, in reality other losses limit the performance of solar cells: these can be split into *optical* and *electronic* losses.

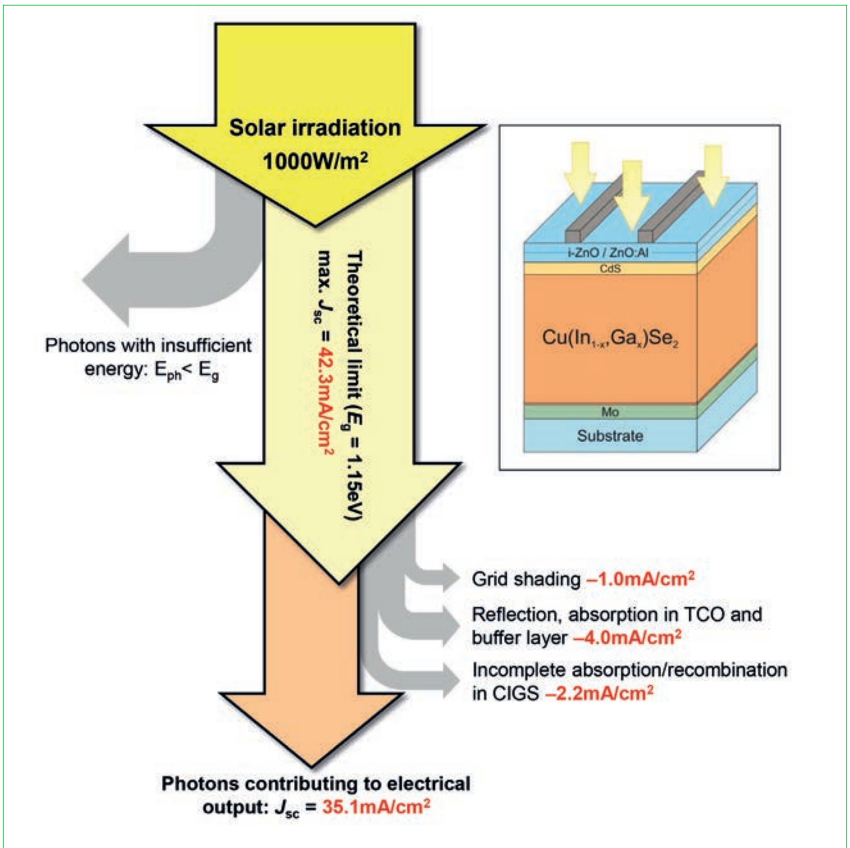


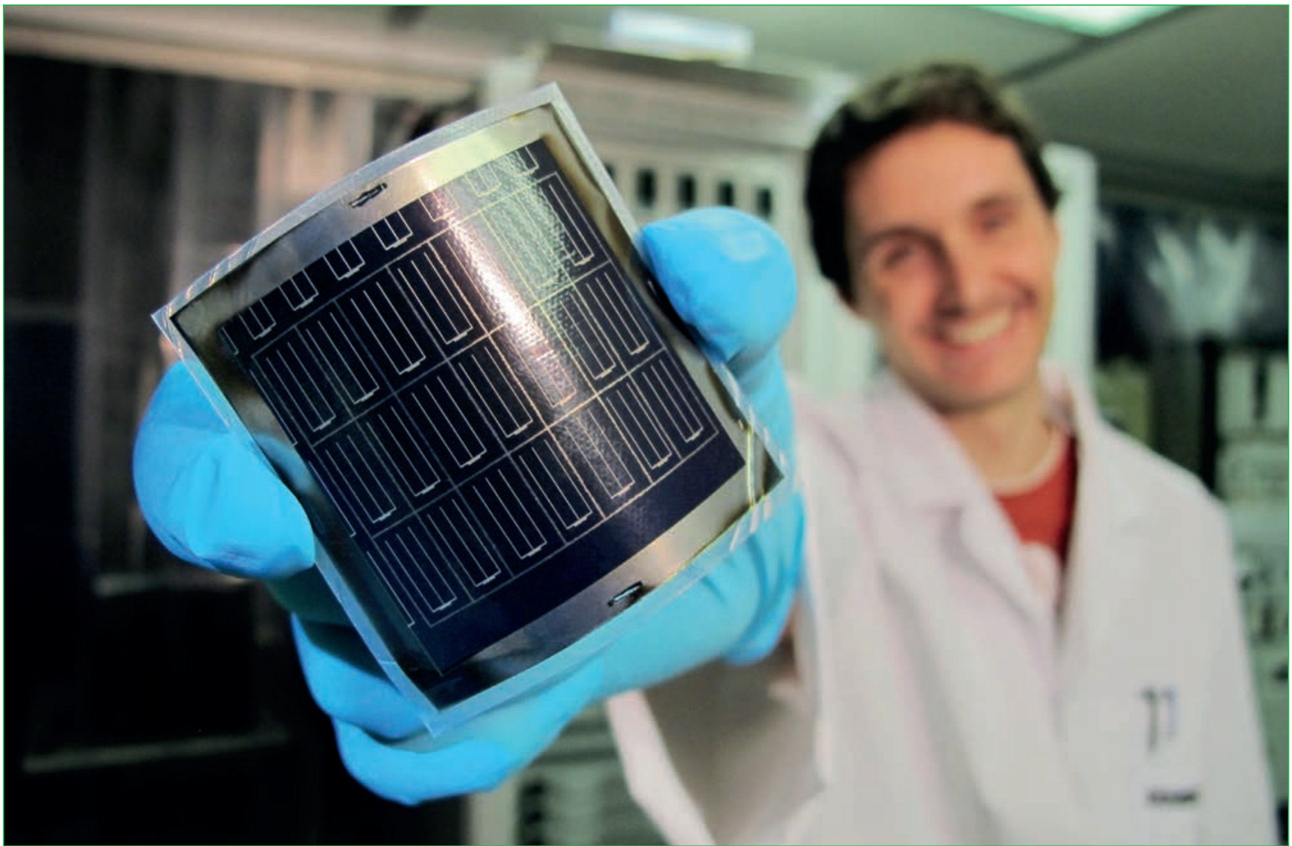
Figure 3. Illustration of the remaining J_{sc} losses in state-of-the-art CIGS solar cells. The inset shows a schematic of a CIGS solar cell cross section.

In a CIGS device, optical losses arise because of reflection at the surface, parasitic absorption of photons in the TCO and the buffer layer, and incomplete light absorption in the CIGS layer. The individual losses for a device produced at Empa with an efficiency of 20.4%, and using a CdS buffer layer, are quantified in Fig. 3. With an absorber band gap of 1.15eV, a maximum short-circuit current density (J_{sc}) of 42.3mA/cm² can be achieved in an ideal situation. As shown in Fig. 3, the most severe optical losses in a CIGS device occur as a result of parasitic absorption in the TCO and buffer layers. To eliminate, or at least reduce, the influence of the TCO on the optical losses, suitable materials with higher optical band gaps and higher mobilities are required. This is a big challenge for future research because several factors need to be considered: the optoelectronic properties, the limited deposition temperature the device can withstand (<200°C), and the price of materials.

"The most severe optical losses in a CIGS device occur as a result of parasitic absorption in the TCO and buffer layers."

As regards the buffer layer, a lot of effort has been put into replacing CdS by a material with a larger band gap, such as Zn(O,S); Solar Frontier recently demonstrated that a very high efficiency of 20.9% can be achieved [18] this way. Another, even more challenging, approach would be to completely redesign the CIGS device structure in the direction of a rear-contact solar cell with a passivated front surface, so that the TCO and buffer layers can be completely omitted and both contacts are located on the back side. Such an approach has already been successfully applied to Si-based solar cells. To apply this concept to a CIGS absorber layer, however, the quality of the material needs to be further improved, because a long diffusion length of the generated charge carriers is necessary, so that they can reach their respective electrical contacts.

Concerning the electronic losses, which mainly influence the open-circuit voltage (V_{oc}) and fill factor (*FF*) of the solar cells, there is still an ongoing discussion about their actual origin. In general, recombination occurring at defects in the CIGS bulk or at any of its interfaces, or at grain boundaries,



Credit: Empa – Swiss Federal Laboratories for Materials Science and Technology.

Figure 4. Empa flexible CIGS solar cell.

limits the device performance. Much effort is currently being devoted to better understanding each of these mechanisms and to developing new deposition methods and treatments for reducing their influence.

The PV parameters of a device with 20.4% efficiency produced at Empa (Fig. 4) are summarized in Table 1 and compared with the theoretically achievable values in the Shockley-Queisser limit. By overcoming some of the above-described remaining limitations, an improvement in J_{sc} by 10% to 38.5mA/cm^2, in V_{oc} by 9% to 800mV, and in *FF* by 3% to 81% seem feasible. In fact, such values have already individually been reported for this technology. Combining these best individual values in a single device would yield a CIGS solar cell efficiency of 25%. The first step in reaching this ambitious milestone should be to identify the basic properties of the layer and devices, and then design the processing accordingly. Indisputably, process optimization alone is not sufficient for achieving this goal – innovative approaches will also be required.

	J_{sc} [mA/cm^2]	V_{oc} [mV]	*FF* [%]	η [%]
SQ limit (1.15eV)	42.3	887	87	32.7
Empa cell on polyimide	35.1	736	78.9	20.4
Difference relative to SQ limit	–17%	–17%	–9.3%	

Table 1. PV parameters of a CIGS solar cell processed on flexible polyimide substrate by Empa compared with the Shockley-Queisser (SQ) limit values for a single-junction solar cell with an energy band gap of 1.15eV.

Advanced concepts for efficiencies towards 30% with tandem solar cells

A proven concept for enhancing efficiency beyond the values achievable with single-junction solar cells is a multi-junction device (e.g. tandem or triple-junction solar cell). Such a concept has been successfully applied to monocrystalline III-V semiconductors, yielding efficiencies well above 40% under concentrated light. Because of the high production costs, these devices are mainly used in very specialized applications, such as concentrated PV or space projects. In multi-junction solar cells, two or more cells with different energy band gaps are stacked on top of each other in such a way that high-energy photons are absorbed in the top cell and low-energy photons in the bottom one, leading to an optimal use of the solar spectrum. This raises the theoretical maximum efficiency from ~33% for single-junction solar cells to ~44% for tandem solar cells. However, this concept has not yet been successfully applied to polycrystalline thin-film solar cells, mainly because the technology for combining high efficiency and high transmittance for near-infrared light (NIR) is lacking. This may change with the rapidly emerging perovskite solar cell, which has a tuneable band gap between 1.55eV and 2.3eV, making it an ideal candidate for the top cells in combination with CIGS solar cells at the bottom. Certified efficiencies of up to 20.1% have already been achieved for a single-junction perovskite solar cell [10]. For their implementation as top cells in tandem devices, perovskite solar cells with two transparent contacts are currently being developed in order to allow IR light to be transmitted to the CIGS bottom cell.

Different approaches can be used to combine CIGS and perovskite solar cells in tandem devices. The most straightforward is the separate production and subsequent stacking of the devices (Fig. 5); however, this can lead to losses of NIR light in three highly conductive TCO layers. Alternatively, perovskite solar cells can be monolithically grown on CIGS solar cells, which is facilitated by the low processing temperatures

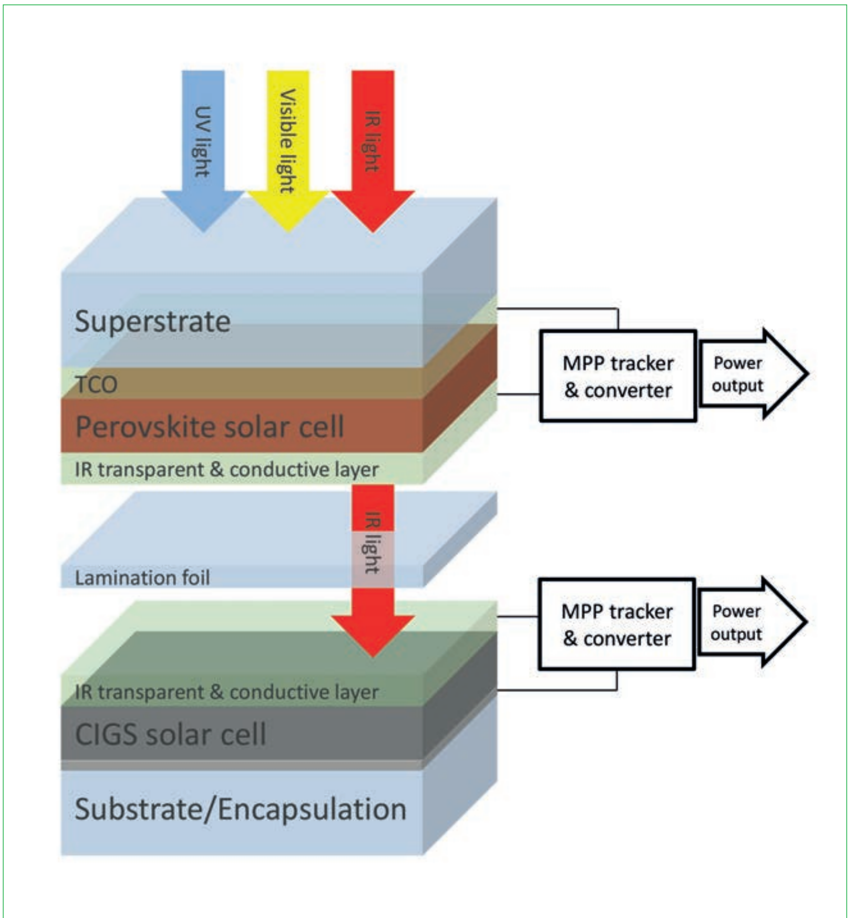


Figure 5. Schematic of a four-terminal, CIGS-perovskite tandem solar cell concept.

(<200°C) for perovskite solar cells. Several methods to prepare CIGS-perovskite tandem solar cells are currently being investigated and that research is expected to lead to these cells demonstrating efficiencies edging towards 30% in the near future [20]. Wafer-based tandem solar cells have shown their merits for better utilization of the solar spectrum, but the development of large-area manufacturable CIGS thin films as the bottom cell will break the bottleneck related to NIR-light loss, potentially leading to low-cost polycrystalline thin-film tandem solar cells.

CIGS from an industrial perspective – market for CIGS

Despite the emergence of several CIGS companies about 15 years ago, the full transfer of lab-scale results to industrial production is still ongoing. The crisis which hit the entire PV industry, mainly due to oversized production capacity, led to the disappearance of a significant number of companies in all types of PV technology in the last three years. The surviving CIGS companies are now scaling up production while still remaining active on the research front with the aim of further reducing production costs and increasing module efficiencies. Solar Frontier is currently the largest CIGS player in the market, with a production capacity of more than 1GWp. Hanergy Group has acquired several CIGS manufacturers – such as Solibro, Global Solar and Miasolé – and is now planning to build up to a 3GWp production capacity within the next few years. A more detailed overview of some of the other active players is given in Reinhard et al. [21].

Key aspects for competitiveness of this technology are higher efficiencies and lower production costs of the modules. Solar Frontier, for example, is targeting to increase its average module efficiency to at least 16% by 2016 [22]. Solibro expects a module efficiency of 17% to be feasible by 2017 [23]. Manz announced a CIGS module production cost of around €0.41/W for a 147MW/annum production line. Bosch projects production costs below $0.38/Wp in a 1GW plant with 16.3% average module efficiency.

Thin-film PV technologies currently make up 8% of the total market, whereas CIGS holds only 2%, but the production volume of CIGS is increasing. Besides ground-mounted CIGS modules, lightweight and flexible products in particular are advantageous for BIPV and rooftop applications. The global market related to buildings is expected to grow from 23GW in 2013 to 33GW by 2017, while there remains a huge market if one considers metal roofs and facades [24]. It is predicted that the building-related CIGS market could achieve an additional 25–30GW by 2020. Flexible and lightweight solar modules can be directly laminated to such metallic building components, resulting in further cost benefits and additional functionality for electricity production.

"The recently achieved efficiency improvements at the solar cell level are a solid basis for constructing CIGS solar modules with efficiencies above 17%."

Conclusions

In summary, the recently achieved efficiency improvements at the solar cell level are a solid basis for constructing CIGS solar modules with efficiencies above 17%. If the research community succeeds in driving solar cell efficiency towards 25%, full-area modules with efficiencies exceeding 20% will be possible. Conceivably, even higher performance is possible with the concept of tandem devices, though this would mean an additional processing line for the top cell. However, provided the production costs are mainly determined by the substrate and encapsulation, this is a viable possibility for creating highly efficient modules and generating low-cost solar electricity. The efficiency targets presented here might appear to be highly ambitious, but from a retrospective look at the historical trend of progress made in CIGS and compound semiconductor thin-film PV, the chances of their realization in the future are high.

Acknowledgement

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About the Authors

Dr. Stephan Buecheler studied physics at ETH Zurich and received his diploma in 2007. After receiving his Ph.D. from ETH Zurich in 2010, he took the position of group leader in the Laboratory for Thin Films and Photovoltaics at Empa, where his research group is currently working on highly efficient CIGS, CdTe and perovskite solar cells, including advanced tandem concepts.

Dr. Fabian Pianezzi studied physics at ETH Zurich and received his master's in 2009. He then joined Empa as a Ph.D. student and focused on characterizing the electronic properties of CIGS solar cells. In 2014 he took up a postdoctoral position in the Laboratory for Thin Films and Photovoltaics at Empa, where his work focuses on solar cell device characterization using advanced diagnostic tools.

Patrick Reinhard studied materials science at ETH Zürich and received his master's in 2011, with a specialization in material properties and analysis. He joined Empa as a Ph.D. student in 2012, and has since been involved in the development of high-efficiency, flexible CIGS solar cells. His work mainly focuses on the bulk and interface modifications of CIGS absorber layers induced by alkali treatments, especially potassium related.

Enrico Avancini received his bachelor's in physics in 2012 from Trento University in Italy and later completed his studies at Freie Universität Berlin, obtaining an M.Sc. in physics in 2014. In November the same year he joined the Laboratory for Thin films and Photovoltaics at Empa as a Ph.D. student.

Dr. Lukas Kranz studied nanoscale engineering at the University of Würzburg, Germany. He conducted his Ph.D. thesis at Empa, where he worked on the development of CdTe thin-film solar cells on glass and flexible metal-foil substrates. In 2014 he became a postdoctoral researcher at Empa, where his research focuses on the development of NIR-transparent perovskite solar cells for application with CIGS in tandem devices.

Fan Fu obtained his master's in materials science from Wuhan University of Technology, China, in 2013, after which he started on his Ph.D. at Empa. His current research is focused on the design, synthesis and characterization of organic–inorganic hybrid perovskite solar cells and exploring the potential of their use in tandem structures in combination with CIGS.

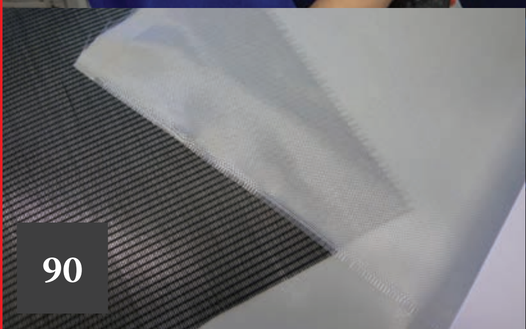
Dr. Ayodhya N. Tiwari received his M.Sc. from the University of Roorkee, India, and his Ph.D. from the Indian Institute of Technology (IIT) in New Delhi. He heads the Laboratory for Thin Films and Photovoltaics at Empa and is a titular professor at the Swiss Federal Institute of Technology Zürich (ETH-Zürich). Prof. Tiwari is a co-founder and the chairman of Flisom AG, a Swiss company involved in the production of monolithically interconnected flexible and lightweight CIGS solar modules.

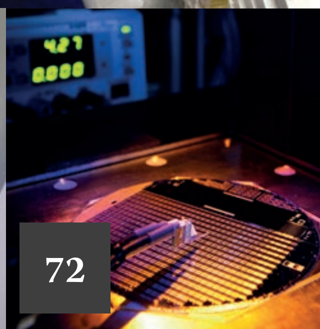
Enquiries

Dr. Stephan Buecheler
Laboratory for Thin Films and Photovoltiacs
Empa, Swiss Federal Laboratories for Materials Science and Technology
Überlandstrasse 129
8600 Dübendorf
Switzerland

Email: stephan.buecheler@empa.ch
Website: http://www.empa.ch

PV Modules





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The importance of optical characterization of PV backsheets in improving solar module power

Salvador Ponce-Alcántara, Alberto A. Vivas Arangú & Guillermo Sánchez Plaza, Valencia Nanophotonics Technology Center, Polytechnic University of Valencia (UPV), Spain

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Production monitoring in PV: Principles, methodology and deployment

Thibaut Lemoine, STS-Certified, Kunshan, China

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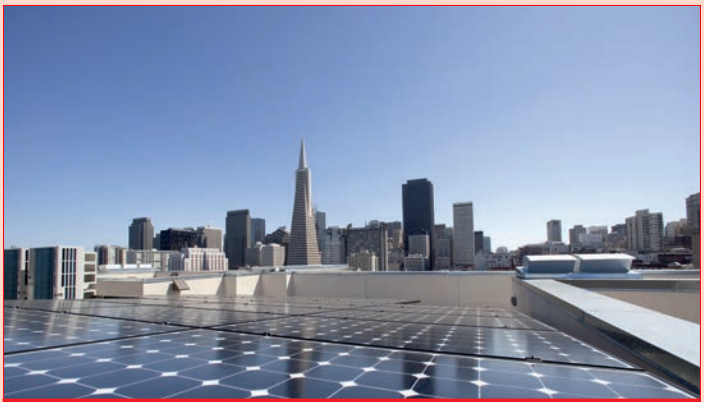
Adapting conventional tabbing–stringing technology for back-contact solar cells and modules

Tom Borgers[1], Jonathan Govaerts[1], Arvid van der Heide[2], Stefan Dewallef[2], Ivan Gordon1, Jozef Szlufcik1 & Jef Poortmans[1]

[1]imec, Leuven; [2]Soltech, Tienen, Belgium

SunPower buys SolarBridge to develop next-gen AC module product offering



SunPower is looking for increased access to commercial and residential markets through its acquisition of SolarBridge.

Source: SunPower

SunPower is to acquire SolarBridge Technologies, a US-based small-cap microinverter firm, for an undisclosed sum. Specialising in integrated microinverter technology, SolarBridge's technology would be developed to operate with SunPower's high-efficiency modules for the residential and commercial rooftop markets, according to SunPower.

According to a senior analyst with IHS, Solarbridge was the third largest microinverter supplier to the United States in revenue terms in 2013.

IHS forecasts that AC modules will be the fastest growing microinverter type, growing over 100% per year to reach over 800MW in 2018, as they significantly reduce 'soft costs' such as labour which currently makes up a significant proportion of total system costs in the United States. SolarBridge highlighted during the week of Solar Power International in October that it had conducted a select survey of US installers that noted the challenges for installers in selecting the best technology for applications due to the vast hardware choice in the market.

New and emerging markets

CSUN expands 'go-to-market capabilities' in Turkey

PV manufacturer China Sunergy (CSUN) has signed a memorandum of understanding (MOU) with Deniz Finansal Kiralama (DenizLeasing) that will see the pair offer solar through leasing in Turkey.

According to the MoU, DenizLeasing, a subsidiary of DenizBank Financial Services Group, will assist and provide capital leasing for PV projects as large as 100MW, deploying CSUN's solar modules and other components. In October, CSUN completed the delivery of 39MW of solar modules to Third Step France, for projects in France from CSUN's plant in Turkey which the company opened in early 2013.

Trina Solar eyes new markets and gains UK certification

Tier-one Chinese module manufacturer, Trina Solar, supplied 7.8MW of its 31,200 Honey modules for ten rooftop projects in Thailand at the beginning of November, while the company also opened a warehouse in South Africa at the end of the previous month.

The South Africa expansion is part of partnership with a local logistics company already well established in the country. Trina said that new facility would increase the company's local footprint and improve its services and support in South Africa, expanding on its previous operations in imported stock, stored in containers.

The Thai rooftop PV installations will be some of the first distributed rooftop installations since the introduction last year of Thai National Energy Policy Commission (NEPC)'s feed-in tariff for rooftop installations.

Also during November, Trina was awarded a Carbon Footprint Verification from international certification body, the British Standards Institution for its PV production cycle.

ReneSola expands into Canada and Mexico

Major tier-one PV manufacturer, ReneSola, has expanded into Canada and Mexico. The company is already active in the US and has now opened warehouse and office facilities in Mexico City and Mississauga, Ontario.

The company cited the gap between Mexico's renewable energy target of 35% by 2024 and the 4% figure recorded for solar, wind and geothermal in 2012. Meanwhile Ontario, Canada's dominant solar market, has eliminated its domestic content requirement for the third phase of its feed-in tariff programme.

However, at the end of November ReneSola reported lower than expected third quarter results and guided full-year module shipments, down by at least 540MW compared to previous projections. The company made PV module shipments totalling 462.2MW in the third quarter, compared to 498.7MW in the previous quarter.

The lower shipments were said to be due a delay in shipments caused by new lower minimum imported prices in Europe, which were only announced towards the end of the quarter.

Canadian Solar's Americas push

Canadian Solar has made gains in the Latin American markets of Honduras and Brazil. The company signed a 146.4MW module supply deal to two projects in the former in mid-October before emerging from a recent reverse auction in Brazil with 114MW worth of projects for a local developer in Minas Gerais.

Canadian Solar said that it secured PPAs at US$86.42/MWh for the Brazil projects, in auction which was massively oversubscribed. Additionally the company's attempts to target the US as a key market both in module supply and PV plant construction received a boost as Canadian Solar qualified to supply installer Sunrun with modules.

Chinese manufacturers' shipment fortunes

JA Solar module shipments increase 55.6% sequentially; sold out in Q4

JA Solar reported a 55.6% increase in module shipments in the third quarter of 2014 and generated revenue of US$492.2 million, up 24.7% sequentially. The company reported total shipments of 785.4MW, a 57.0% year-on-year increase and 15.2% higher than the previous quarter and above the high end of the previously announced guidance of 730MW to 760MW.

It guided total cell and module shipments to be in the range of 850MW to 900MW in the fourth quarter, with full-year 2014 shipments expected to be in the range of 3.1GW to 3.2GW. JA Solar said it expected to ship 160MW of modules to its downstream projects, compared with the previously guided 200MW. Recent shipments included 100MW of PV modules to the Quaid-e-Azam Solar Park in Pakistan, under the supervision of PV Lab Germany GmbH. The modules underwent tests including Electroluminescence Inspection and the 3×IEC Standard Thresher Test.

Yingli Green slashes full-year module shipment guidance

At the end of November, Yingli Green Energy slashed full-year module shipment guidance that indicates almost zero shipment growth for 2014.

Yingli Green guided shipments to be in the range of 3.30GW to 3.35GW, down from last quarter's revised guidance of shipments of 3.6GW to 3.8GW.

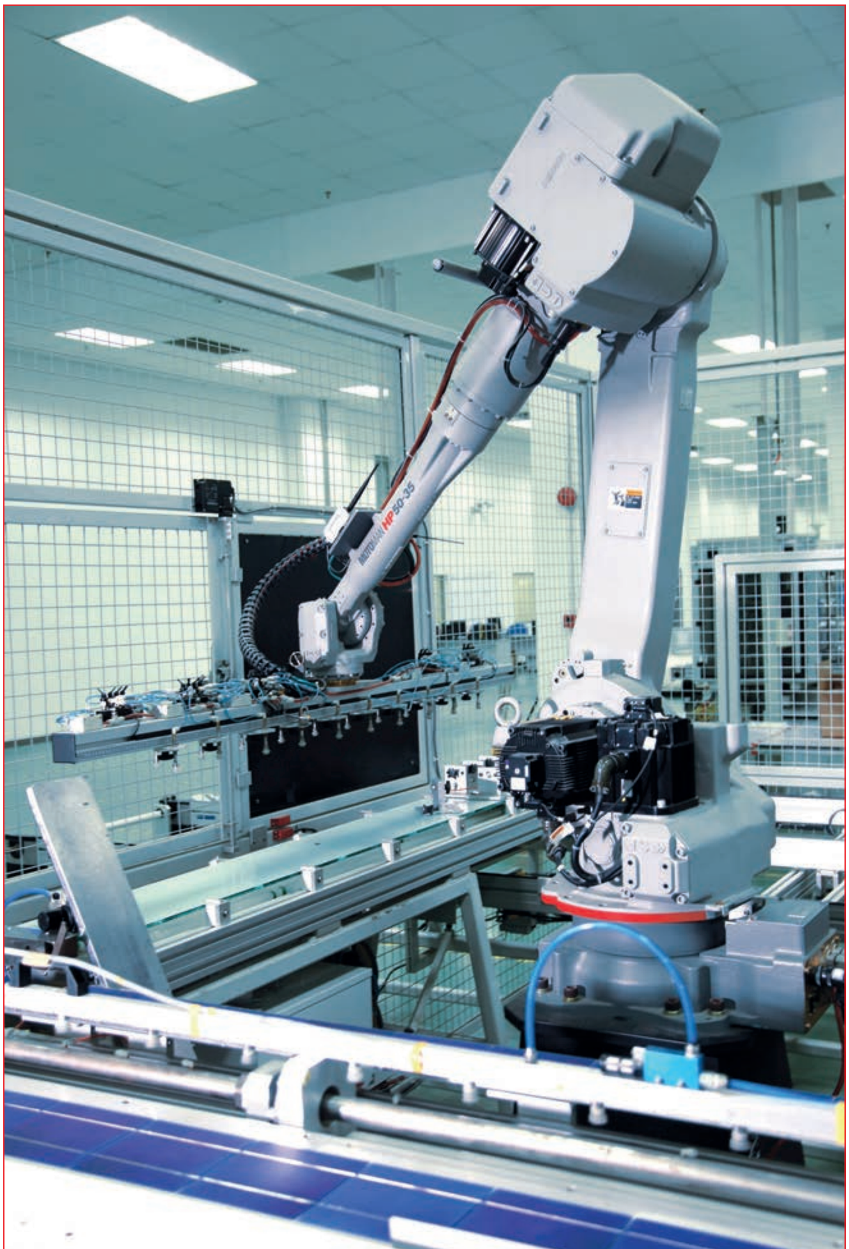
As a result, Yingli Green's 2014 shipment growth is only 3% to 4.6% compared to 2013. Yingli Green had started the year with full-year shipment guidance of 4.0GW to 4.2GW. "In order to seek a balance between our shipment volume and profitability, we decided to revise our shipment guidance for full year of 2014 to 3.3-3.35 GW," said Liansheng Miao, chairman and chief executive of Yingli Green Energy.

JinkoSolar expects over 1GW of shipments in Q4 after record Q3

JinkoSolar reported a record high 758.1MW of module shipments in the third quarter of 2014, while guiding shipments of over 1GW in the fourth quarter. Key shipment growth was in China, up 81.4% compared with the previous quarter.

JinkoSolar guided total solar module shipments in the fourth quarter of 2014 to be in the range of 1,030MW to 1,120MW, which is expected to include 730MW to 770MW of module shipments to third parties and 300MW to 350MW for its own downstream projects.

For the full year 2014, JinkoSolar is estimating that total solar module shipments will be in the range of 2.9GW and 3.2GW, which would include 2.3GW to 2.5GW of module shipments to third parties. In the past few months JinkoSolar has made or announced significant shipments to projects in territories including Chile (19MW), the USA (40MW) and India.



JA Solar reported a 55.6% increase in module shipments in Q3 2014.

Certifications and documentation

WINAICO targeting US commercial and utility markets with 1000V UL certification

Taiwan-based specialist PV module manufacturer, WINAICO, has received US 1000V UL certification for its WST and WSP-series high-efficiency modules. The company will target growing demand in the US commercial rooftop and utility-scale ground-mount sectors for PV plants with higher system voltage levels, using longer module strings to lower cost, and simplify, balance of system (BOS).

WINAICO's WST modules recently also passed TÜV Rheinland's toughest PID (Potential Induced Degradation) test with minimal degradation. Additionally, Both WST and WSP were awarded Japan Electrical Safety and Environment Technology (JET) certifications in November.

Vikram Solar modules win two key US certifications

Indian tier-one module manufacturer, Vikram Solar, has won two key US certifications for its 60-cell polycrystalline modules.

The Kolkata-based manufacturer has UL 1703 certification for the 240-270W modules with clear frame and white backsheets. The panels were also added to the California Energy Commission's list of eligible products for its Million Roofs policy, initiated by former state governor Arnold Schwarzenegger.

The company recently also boosted its credentials in the UK, completing OST Energy's factory and product audit.

Suntech bolsters warranty with Munich Re-backed insurance

Suntech has bolstered its warranty with the addition of insurance coverage by China-based Ping An and reinsured by Munich

Source: Fraunhofer ISE Alexander Wekkeli

Soitec has beaten its own CPV cell record with a 46% conversion efficiency.

Re. The new insurance policy will provide 25 years of cover against any significant drop in module performance.

Suntech's modules have also undergone an additional technical review by UK-based OST. August Proebstl, head of corporate insurance partner, Munich Re, said the insurance solutions "sets industry standards by being the first significant deal when it comes to volume insured and indemnity offered to a manufacturer domiciled in the People's Republic of China".

Company news

LDK Solar's management regains control from liquidators

The joint provisional liquidators (JPLs) of Cayman Islands-registered LDK Solar are to hand back management of the bankrupt firm to its regular management.

The JPLs noted that the bankruptcy schemes of arrangement, filed in both the Cayman Islands and Hong Kong, were now in place and sanctioned by the relevant courts, meaning the powers of the JPLs had now mostly been suspended.

As of 10 December, LDK Solar's directors were in charge of the company, the JPLs said. The consummation of the restructuring transactions is expected to occur on 17 December, 2014. Bankruptcy proceedings are also underway in the US.

GCL New Energy details major PV module deal with Chaori Solar

In early December, GCL New Energy subsidiary, Nanjing GCL New Energy, revealed a PV module purchase deal with bankrupt Shanghai Chaori Solar as part of GCL New Energy's plans to acquire a 30% stake in the company and save it from liquidation.

Chaori Solar is supplying orders totalling around 366MW and valued at around US$236.6 million, with two orders priced at US$0.65/W and the remaining larger orders priced at US$0.64/W.

GCL New Energy was mildly rebuked for late reporting of the news to the Hong Kong Stock Exchange. The company also recently announced plans to dispose of its wafer production business, which now has a nameplate capacity of 13GW.

REC Solar to go private following sale

Module manufacturer REC Solar is to be liquidated and delisted following its US$640 million sale to China's Bluestar Elkem, announced in November.

Following its integration with the polysilicon producer, REC Solar will be liquidated under Norwegian law and the proceeds distributed to the company's shareholders. REC Solar said shareholders could expect to receive NOK107 (US$15.66) per share.

The move would make REC Solar one of the world's largest private module manufacturers, with only Japan's thin-film specialist Solar Frontier coming close. The news follows the October announcement of two supply agreements totalling 300MW for REC Solar's 'Peak Energy 72 Series' of panels to US developer Recurrent Energy and an expanded 220MW deal with SolarCity.

Soitec flies flag for CPV

Soitec-Fraunhofer ISE multi-junction CPV cell hits world record 46% conversion efficiency

A Soitec multi-junction cell for concentrator photovoltaic (CPV) systems has become the company's latest to reach a world record for conversion efficiency at 46%. Germany-headquartered research institute Fraunhofer ISE collaborated with Soitec on the new cell, along with CEA-Leti, a division of the French research and technology organisation.

The efficiency of the new cell, revealed in December, has been independently verified under standard test conditions by the Japanese National Institute of Advanced Industrial Science and Technology (AIST). Efficiency was measured at a concentration of 508 suns under a Fresnel concentrator lens.

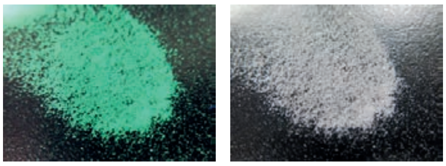
Soitec gets 150MW CPV deal

Soitec Solar Development, a subsidiary of semiconductor manufacturer Soitec, has agreed a 150MW module deal with a North American PV energy provider. The customer has a power purchase agreement with San Diego Gas & Electric (SDG&E) for the solar project in California.

Construction of the facility will revolve around certain conditions related to the deal, but once operational, the project will utilise of 83,400 CPV modules manufactured at Soitec's San Diego factory.

Product Reviews

Hitachi



Wavelength conversion particles from Hitachi Chemical boost cell efficiencies by over 2%

Product Outline: Hitachi Chemical has begun sales of wavelength conversion particles (WCP) for solar encapsulant sheets that help increase the conversion efficiency of solar cell power generation. WCP series contains specialized phosphor within acrylic resin and converts short wavelength light (ultraviolet light) into long wavelength light (visible light).

Problem: Manufacturers of solar cells and materials are concentrating their efforts on addressing the issue of how to improve conversion efficiency by increasing power generation from a limited amount of sunlight, while retaining existing machinery and processes.

Solution: Hitachi Chemical has developed wavelength conversion particles for solar encapsulants that help increase power generation conversion efficiency.

The WCP works by converting short wavelength light (ultraviolet light) that could not previously be used into long wavelength light (visible light). Solar cell modules that use solar encapsulant sheets (wavelength conversion film) made of these particles are expected to increase conversion efficiency by up to around 2.2%, according to solar cell modules using conventional solar encapsulants in outdoor tests that comply with JIS C 8919. These particles are also dispersed throughout acrylic resin and are claimed to have outstanding durability.

There is no need to alter the manufacturing process when these particles are mixed into solar encapsulant sheets by manufacturers, which contributes to an increase in conversion efficiency without affecting productivity. In addition to solar cells, this technology can be adopted to add new functionality to counterfeiting protection, identification of authenticity, optical materials and other applications through the use of wavelength conversion.

Applications: Solar cell/module encapsulant to boost conversion efficiency.

Platform: WCP series contains specialized phosphor within acrylic resin and converts short wavelength light (ultraviolet light) into long wavelength light (visible light). Existing PV module assembly lines can be adapted.

Availability: Currently available.

TÜV Rheinland and DB Schenker

TÜV Rheinland and DB Schenker develop advanced PV module logistics system

Product Outline: DB Schenker and TÜV Rheinland have developed a new monitoring system for preventing and discovering transport damage, as well as monitoring transport and validating the performance of photovoltaic modules.

Problem: Until now, there has been no transparency regarding damage to photovoltaic modules that may have been caused by transport and the long-term effects this damage has on the energy yield of these products. However, industry experts estimate that transport has an unnecessary and detrimental effect on between 5% and 10% of all modules, impairing their performance. Damage to modules often remains undetected if it is not apparent at first glance or it cannot be traced back to its origin later on when it is discovered.

Solution: The newly developed monitoring system serves to ensure quality in major projects by revealing damage caused by rough handling or environmental influences arising during transport. The system comprises three key steps: First, the transport packaging and quality processes in production are tested and the shipping unit certified. Second, the procedures for taking outgoing measurements and the equipment used to assess the performance and the quality of the products upon leaving the factory are optimized and inspected. Third, transport is continuously monitored and a technical inspection is conducted on the delivered products in DB Schenker's receiving warehouse upon market entry into the European Union or other global target markets.

Platform: All measurement data and other necessary pieces of information are stored in sufficient resolution in a database that is accessible to the delivery recipient. DB Schenker's containers are fitted with specialized shock and vibration sensors that have been audited by TÜV Rheinland. At the same time, information about the current location of the delivery is provided via GPS. In addition, a statistically calculated representative spot check of the delivered modules is conducted in DB Schenker's receiving warehouse.

There, TÜV Rheinland collaborates with the logistics service provider to operate a measuring station in which insulation tests, flasher measurements and electroluminescence analyses are also conducted following the visual inspection. Once the comprehensive analyses are complete, TÜV Rheinland independently certifies the logistics processes at each manufacturer's plant.

Availability: Currently available.

The importance of optical characterization of PV backsheets in improving solar module power

Salvador Ponce-Alcántara, **Alberto A. Vivas Arangú** & **Guillermo Sánchez Plaza**, Valencia Nanophotonics Technology Center, Polytechnic University of Valencia (UPV), Spain

ABSTRACT
With the objectives of reducing cell-to-module losses, improving module efficiency and reducing the price per watt, increasing importance is being placed on the optical properties of backsheets. It is assumed that a higher reflectance backsheet allows a better reuse of incident sunlight. However, this statement is not always true: another factor must be taken in account, namely the angular dependence of the reflected light. In this regard, backsheets with a high specular component deviate from the ideal Lambertian reflectance, resulting in a minor increase in module current. As a result, differences can be found in module power because of the use of backsheets with similar global reflectance but different angular components of reflected light. A total of 33 industrial backsheets with Tedlar, Kynar, EVA and PET layers from different suppliers were analysed. A comparison of backsheets with low and high global reflectances revealed that the power variation in a standard PV module reaches 0.54% abs. In the same vein, and for backsheets with similar global reflectances, it was experimentally found that the angular response of the reflected light was responsible for a power difference of 0.22% abs. in a standard module.

Introduction
PV backsheets play a very important role in ensuring a solar module lifetime of 25 years or even longer. They have the function of protecting the solar cells, the metallic contacts and the encapsulant against ultraviolet radiation, as well as against the penetration of water vapour and moisture from the atmosphere. Moreover, and with regard to module efficiency, the global reflectance is a significant factor in reducing cell-to-module losses and improving module efficiency.

> "PV backsheets play a very important role in ensuring a solar module lifetime of 25 years or even longer."

From an optical point of view, a ray of light which falls on a PV module can be reflected, absorbed or transmitted by any of its components. McIntosh et al. [1] and Jaus et al. [2] demonstrated that, as shown in Fig. 1, incident rays of light can be absorbed by the glass (2), the encapsulant (4), the solar cell (5) and the backsheet (7). Additionally, incident rays reflect from the air–glass (1), glass–encapsulant (3), encapsulant–solar cell (6) and encapsulant–backsheet (8) interfaces and from the front-side metallization of the solar cell. The reflection is often diffuse, particularly in the case of the backsheet, leading to a reuse of some of the reflected light because of a total internal reflection at the glass–air interface. Finally, depending on the thickness and the composition of the backsheet layers, some of the incident light can be absorbed by and transmitted from the PV module. In either case the light will not contribute to an improvement in the current of the solar cells present in the PV module.

Backsheets can be transparent or have different colours, depending on the location where the PV module will be installed. In general, the backsheet is white because of the higher reflectance and to make better use of the light falling on the module.

With regard to the layers that form the backsheet, the three main options offered on the market are:

- **Double fluoropolymer**: This consists mainly of outer layers of Tedlar polyvinyl fluoride (PVF) films, or of Kynar polyvinylidene fluoride (PVDF) films, and a core layer of polyethylene terephthalate (PET). The molecular structure of fluoropolymers is based on a chain of carbon atoms completely surrounded by fluorine atoms, which are responsible for a better protection of the atom chains present on the layer [3]. In terms of price, these kinds of backsheet are the most expensive.

- **Single fluoropolymer**: One way of reducing the cost of the backsheet while maintaining satisfactory behaviour and durability is to reduce the number of fluoropolymer layers from two to one. In this case, the layer structure is formed mainly with

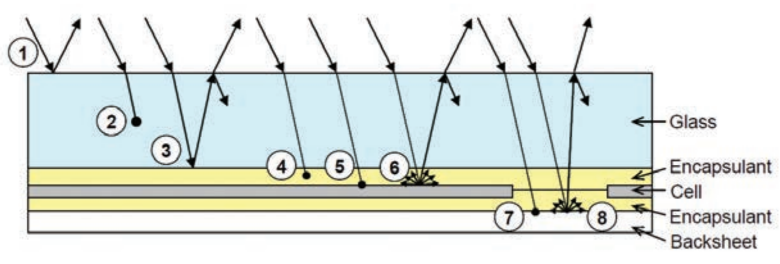


Figure 1. Cross-sectional diagram of a conventional PV module (to scale), and optical loss mechanisms [1].

Tedlar or Kynar on the air side, and with PET and primer or EVA layers on the inner side.

- **Non-fluoropolymer**: This consists of two PET and one primer or EVA layers, and is the cheapest option. In the past it was not considered because of the possible degradation under UV exposure or hydrolysis over long periods of time [4]. However, significant advances in polyester chemistry and production engineering have led to the development of highly UV-durable polyester films.

With these different possibilities in mind, a study was carried out of the optical performance of various white backsheets of each type and the influence on the short-circuit current (I_{sc}) of a PV module; the results are presented in this paper.

It is generally accepted that the short-circuit current and power of a PV module varies proportionally with the global reflectance of the backsheet [5]. In this paper it will be demonstrated that this statement is not always true: another parameter needs to be taken into account, namely the angular response of the light reflected by the backsheet.

Reflectance components of a PV backsheet

A large percentage of the incident light on a white backsheet is globally reflected. That global reflectance has two components: specular and diffuse. In order to reuse a large amount of the light which falls on the backsheet, the diffuse component is more relevant. In this respect, the percentage of the incident light that can be reused by the solar cell depends to a significant extent on the angular dependence of the light reflected in the backsheet.

According to Fig. 2, for a ray of light which falls perpendicularly on the PV module – and taking into account the refractive indices n of the encapsulant, glass and air – Snell's law shows that the critical angle θ for achieving a total internal reflection (TIR) is given by:

$$\theta = \arcsin\left[n_{air} / n_{glass\text{–}EVA}\right] \qquad (1)$$

For glass and encapsulant with a refractive index of 1.5, the internal reflectance angle θ at the glass–environment interface must be greater than 42° in order to redirect a ray of light to a solar cell. For smaller angles, most of the light escapes from the PV module and does not contribute to an increase in the current of the solar cells.

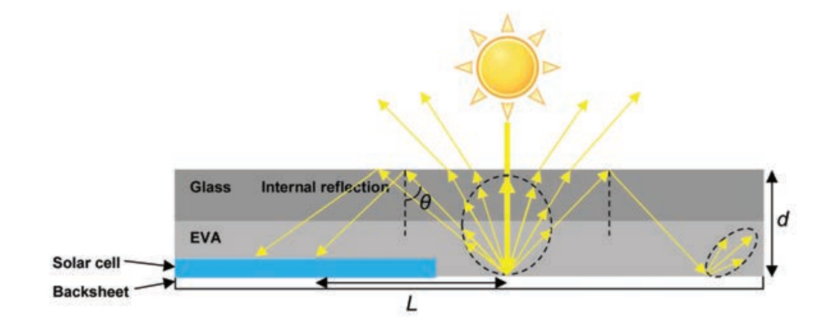


Figure 2. Cross section of a conventional PV module.

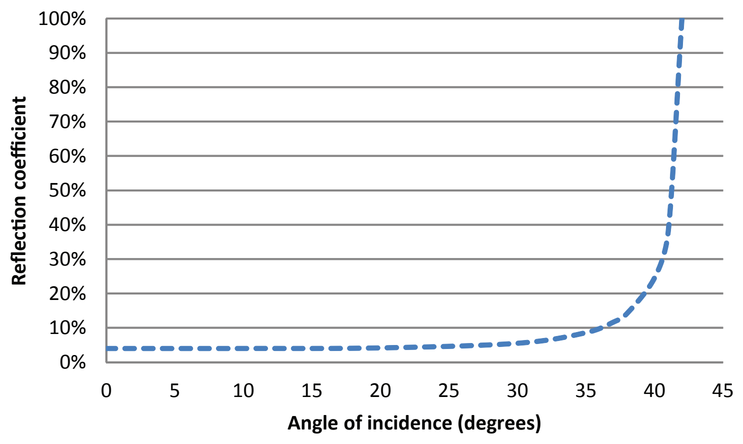


Figure 3. Reflection coefficient as a function of the angle of incidence for a non-polarized ray of light at the glass–air interface.

If d is the combined glass+encapsulant thickness, the length L travelled by the diffused light inside the module is:

$$L = 2 \times d \times \tan\theta \qquad (2)$$

Fig. 3 shows the percentage of light that is internally reflected at the glass–air interface for a ray of light which strikes at a given angle of incidence with respect to the normal of the glass. The percentages have been calculated using Fresnel equations [6], and assuming no polarization of the light reflected at the backsheet.

With those ideas in mind, and if the origin is taken to be the point where the beam spot falls on the white backsheet of a PV module, the reflected light has the following behaviour:

1. According to Equation 2, and as presented in Fig. 2, there is a first circle of light of radius $L/2$ associated with the incident photons that will be reflected and escape from the PV module. The intensity of the circle is highest at the centre (specular component), and decreases with increasing distance from the centre.

2. In addition, because of the total internal reflection of a ray of light striking the interface between the glass and the air at an angle greater than 42°, the reflected light will again fall on the back side of the PV module (the solar cell or the backsheet), defining a new circle of radius L. The intensity of light decreases with increasing distance from the centre of the circle.

3. No light is expected between the two circles, with the exception of Fresnel reflections of light for angles below the critical one, as shown in Fig. 3.

Fig. 4 reveals the above behaviour of a PV module; a green laser was used as a punctual source of light because of the human eye's higher sensitivity to this colour.

The higher or lower intensity of reflected light in each region depends on both the global reflectance and the angular dependence of the light reflected at the backsheet. As a consequence, this significantly affects the percentage of reflected light that can be reused for the solar cell in a PV module.

Reflectance measurements

In order to increase the efficiency of a PV module, the reflectance $R(\lambda)$ of a backsheet is of relevance. In this respect, the optical performance of 33 different backsheets with double, single and non-fluoropolymer layers was analysed. The global reflectance was measured using a SpecWin Light CAS 140CT spectrophotometer and an Instrument Systems 150mm integrating sphere. Equation 3 was used to calculate the effective reflectance R_{eff} between 400 and 1100nm under an AM1.5G solar spectrum; this is used to compare the backsheets and to calculate the influence of reflectance on current variation in a PV module.

$$R_{eff} = \frac{\int R(\lambda) AM\,1.5G(\lambda)\mathrm{d}\lambda}{\int AM\,1.5G(\lambda)\mathrm{d}\lambda} \quad (3)$$

Fig. 5 shows the effective global reflectance under an AM1.5G solar spectrum as a function of the cell-side layer of the backsheet. There is a large variation in effective reflectance, mainly depending on the type of backsheet cell-side layer; in general, white EVA seems to be the best choice. Furthermore, for backsheets with the same layers, large differences in measured global reflectances are also observed, implying that the backsheet fabrication process has a large influence on the final reflectance.

It is clear that the backsheet global reflectance is related to the short-circuit current of the PV module: higher global reflectances usually lead to higher short-circuit currents [5]. On the other hand, and as demonstrated by Equation 1, if the specular component is significant, most of the reflected light will escape from the PV module and will not contribute to increasing the current of the solar cells. For this reason, besides global reflectance another aspect needs to be considered: the angular response of the light reflected by the backsheet.

"Besides global reflectance another aspect needs to be considered: the angular response of the light reflected by the backsheet."

Angular measurements

As discussed in the previous section, in order to reuse a high percentage of the incident light and to increase the current of a PV module, it is important to reduce the specular contribution and to increase the diffused component of

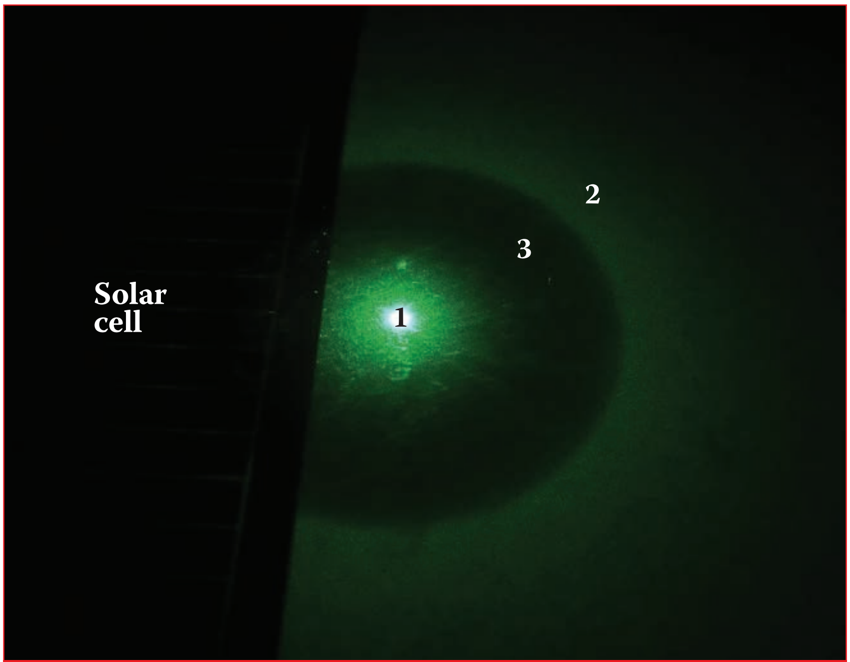


Figure 4. Enlarged photography of the light-reflectance response of a PV module.

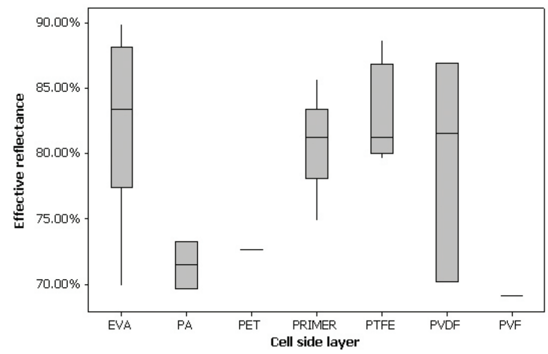


Figure 5. Effective global reflectance of the backsheets analysed. (Cell-side layers: EVA – ethylene vinyl acetate; PA – polyamide; PET – polyethylene terephthalate; PTFE – polytetrafluoroethylene; PVDF – polyvinylidene fluoride; PVF – polyvinyl fluoride.)

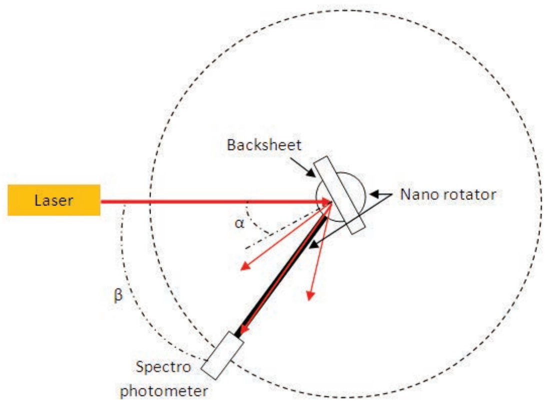


Figure 6. Set-up used to measure the angular dependence of the backsheets. The laser is placed in a fixed position, and the backsheet is put on a rotating base. The base can be rotated from α = 0 to 90°, where α is the angle between the laser beam and the perpendicular to the backsheet; this angle is kept fixed during a measurement. β is the angle between the laser beam and the spectrophotometer, and can vary from 0 to 360°.

the light reflected by a backsheet. In this regard, an ideal backsheet exhibits a Lambertian reflectance. (Lambertian reflectance is the property that defines an ideal diffusely reflecting surface.)

Based on optics components from Thorlabs, an angular measurement set-up (Fig. 6) was used to determine the angular dependence of the light reflected by the backsheets. To measure the angular dependence, both the laser and the backsheet were kept in a constant position. The spectrometer was turned using a Thorlabs NanoRotator 360° rotation stage and an APT precision motion controller. The angular measurement cannot be performed at angles between ±5° respective to the laser location because of the superimposition of the laser beam on the spectrophotometer.

A JDS Uniphase red laser with emissions at 633nm was selected for this study. As well as its stability, the reasons for choosing this laser were that the backsheet has a high reflectance at 633nm, and the maximum value of the external quantum efficiency of a standard crystalline silicon solar cell occurs near that wavelength.

On the basis of average global reflectance and layer structure, different backsheets with similar global reflectance were chosen for this study. In addition, various laser beam angles of incidence with the backsheet were selected: α = 5°, 40°, 60° and 70±2° (low-gloss to high-gloss regions respectively). Represented values are relative to the maximum reflectance measured for an aluminium foil.

The analysed backsheets can be split into three groups, depending on the level of specular reflection: A = high, B = medium and C = low. Fig. 7 depicts the angular response of representative backsheets with these characteristics; a photograph of the reflected light is shown on the right in each case.

According to Fig. 7(a), backsheets from group A have a notable specular component, which increases slightly with the incident angle of the light. As presented in Fig. 7(b), the specular peak of a backsheet from group B has a smaller intensity and is wider compared with the angular response of

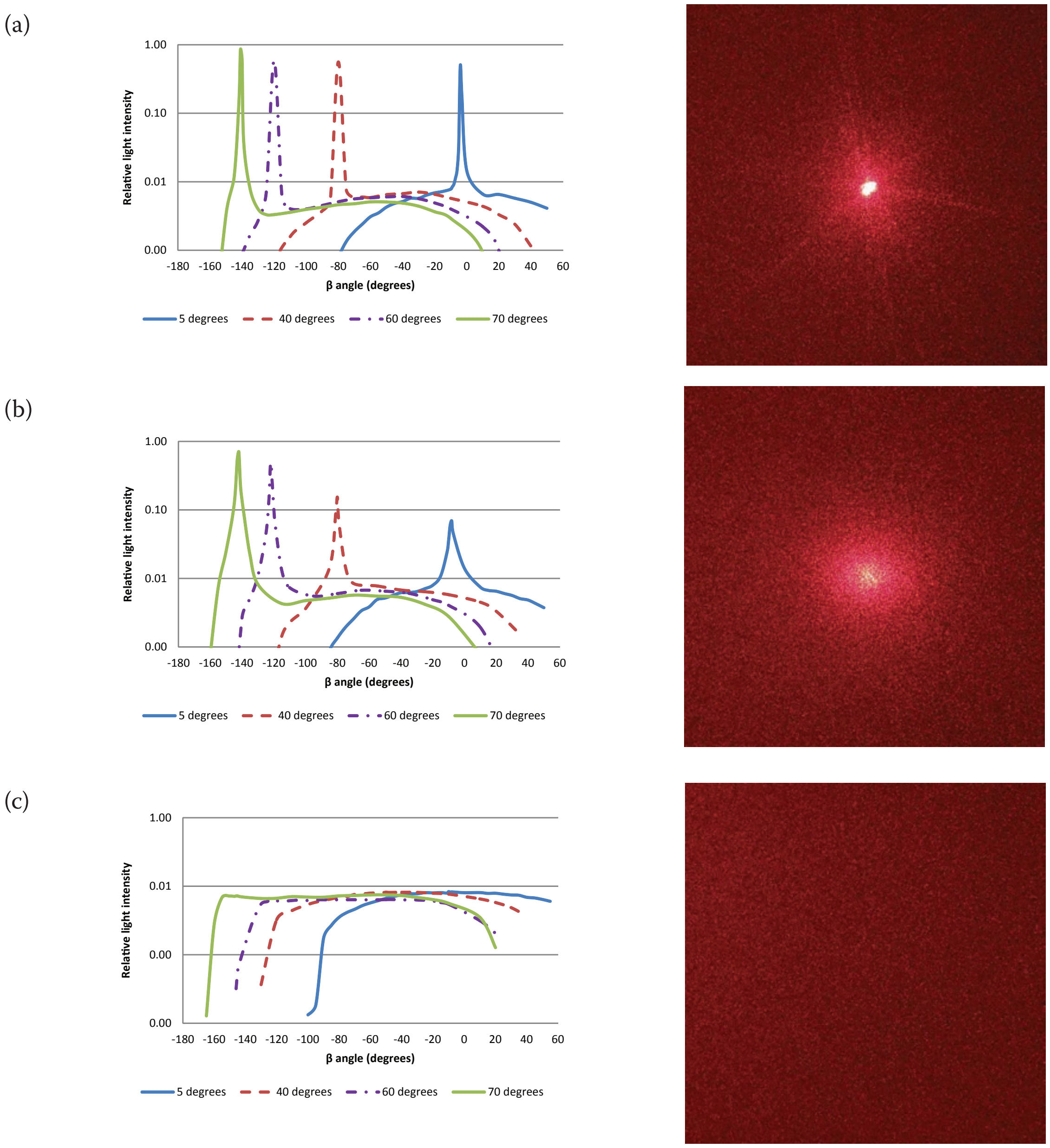


Figure 7. Angular distribution profiles for a backsheet with (a) high specular reflection (group A); (b) medium specular reflection (group B), and (c) low specular reflection (group C). The photograph on the right in each case shows the reflected light for an incident angle of 5°.

a backsheet from group A; moreover, the diffuse component has a higher relevance. When the incident angle of the light increases, the specular peak increases, whereas the diffuse portion decreases. Backsheets from group C have a Lambertian distribution for any incident angle, as seen in Fig. 7(c). Because of this, no specular peak is observed, and the reflected light is notably diffuse. Backsheets with EVA and fluoropolymer cell-side layers dominate in this group.

For a quasi-normal incidence of light (α = 5°), the cumulative reflectance of a representative backsheet from each group was calculated by integrating the measured light over the 2π solid angle; the trends achieved are shown in Fig. 8, along with the cumulative reflectance of an ideal Lambertian reflector [7].

Table 1 shows the expected percentage of light that is subjected to TIR in a PV module for each of the backsheet groups (taking into account the Fresnel reflections and the fact that TIR occurs for a ray of light reflected by the backsheets at angles greater than 42° with respect to the normal).

According to Table 1, the highest expected percentage of reflected light that is subjected to TIR is 52±2%. This value obtained experimentally is close to 56%, which corresponds to the theoretical value estimated by McIntosh et al. [8] for a Lambertian reflector embedded in EVA and glass. For backsheets with similar analysed global reflectances, there is significant variation in the percentages of light that are subjected to TIR. Comparing the backsheet having the highest specular component with that having the lowest one, the difference is almost 9% abs.

Moreover, and without considering multiple reflections, the total incident light on a backsheet that can be reused in a PV module depends on the backsheet's global reflectance. If both the global reflectance effect and the angular dependence of the light reflected by the backsheet are taken into account, the percentage of reflected light that can be reused is obtained using Equation 4:

$$\text{Reused light (\%)} = R_{\text{eff}} \int_0^{90} RC(\alpha) CR(\alpha) \mathrm{d}\alpha \qquad (4)$$

where R_{eff} is the effective reflectance (see Equation 3), $RC(\alpha)$ is the reflection coefficient for a glass to air interface, and $CR(\alpha)$ is the percentage of light reflected at the backsheet at an angle α.

The average global reflectivity of the high-reflectance backsheets utilized in this study is 86±2%. Consequently, and using Equation 4, the incident light on the backsheets that can be reused changes from 37.8±4% to 44.7±4%.

The variation in the number of incident photons (N_{gain}) on the solar cell in a PV module is proportional to the incident photon flux (Φ), the spacing area between the solar cells and the light reflected on the backsheet that can be reused:

$$N_{\text{gain}} = \Phi \times \text{Spacing area} \times \text{Reused light} \qquad (5)$$

The short-circuit current of a solar cell is proportional to the incident radiation up to extremely high light intensities, because of the incidence of a larger number of photons on the cell's active area. Further, a modification of the light intensity has an impact on the open-circuit voltage, which changes logarithmically, as well as on the fill factor, because of variations in the cell's internal resistance [9]. Both effects have an impact on the power of the solar cell. Because of the small variation in light concentration due to the effect of the backsheet, both open-circuit voltage and fill factor can be assumed to be constant.

The short-circuit current density (J_{sc}) can be calculated from the equation:

$$J_{\text{sc}} = q \int \Phi_{\text{mod}}(\lambda).EQE(\lambda)\mathrm{d}\lambda \qquad (6)$$

where q is the electron charge, Φ_{mod} is the photon flux taking into account the effect of the photons reflected on the backsheet, and EQE is the external quantum efficiency of the solar cell.

Fig. 9 shows the variation expected in short-circuit current per millimetre of distance between the cells in the case where the solar cell quantum efficiency is kept constant, and only the effect of the backsheet is considered. A low-reflectance backsheet, with a global reflectance of 73±2%, has also been included.

On the assumption of no change in open-circuit voltage and fill factor, according to Fig. 9 a backsheet with a low specular component yields a power improvement of 0.10% abs. per millimetre of separation between the cells over a backsheet with a high specular component. The standard separation between cells in a PV module is 2mm: in this case the theoretical power variation expected between PV modules processed using backsheets having similar global reflectances, but one having a low specular component and the other a high one, is 0.20% abs.

In a similar way, if backsheets with low and high global reflectances are compared, the power variation is 0.18% per millimetre: for a standard PV module with a separation between cells of 2mm, the expected power variation is thus 0.36% abs.

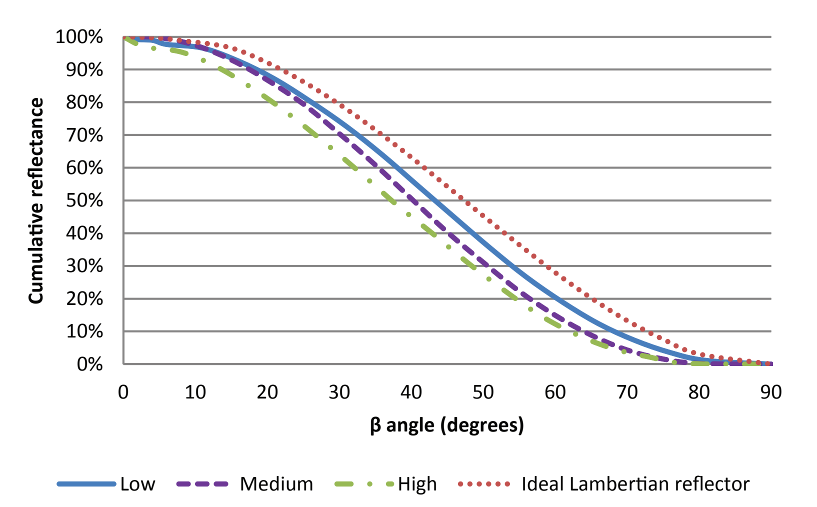


Figure 8. Cumulative reflectance of the selected backsheets with different specular components for a quasi-normal light incidence. An ideal Lambertian reflector is also shown.

Group	Specular component	Expected reflected light that is subjected to TIR
A	High	43±2%
B	Medium	47±2%
C	Low	52±2%

Table 1. Reflected light on the backsheet that can be reused.

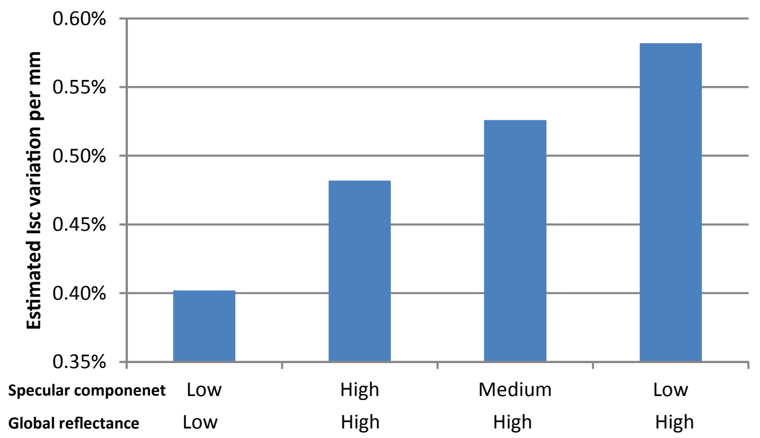


Figure 9. Estimated I_{sc} variation per millimetre of separation between cells for backsheets with different global reflectances and specular components.

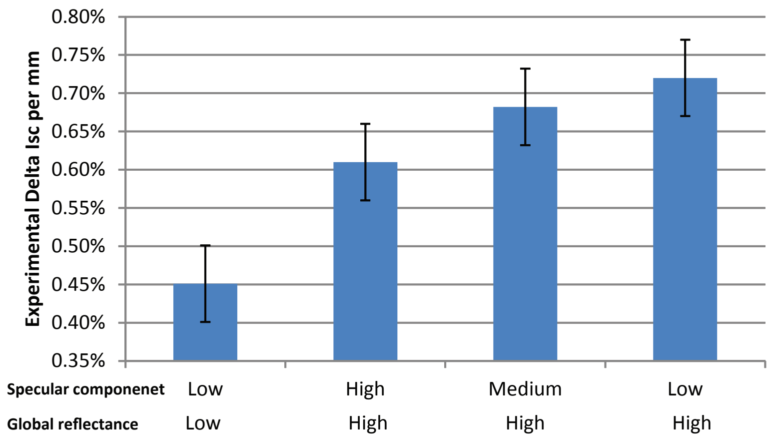


Figure 10. Experimental I_{sc} variation per millimetre of distance between cells.

Experimental study

High-efficiency, 156mm × 156mm × 0.18mm, multicrystalline silicon solar cells with similar electrical parameters were used to study the impact of backsheet optical performance on the short-circuit current of PV mini-modules. PV mini-modules were made up using one solar cell, with the same low-iron PV glass and encapsulant being utilized in each.

Three mini-modules were fabricated for each study group; their electrical characterization was performed under standard test conditions (STC) with an Abet Technologies class A solar simulator. The characterization was carried out using two different black masks: one with the same area as the solar cell, and the second with a separation of 5±0.3mm between the solar cell and the mask edges. Thus, the difference (as a result of the use of one or the other mask) in measured short-circuit current is due to the backsheet effect. At least three measurements were taken in each case.

Fig. 10 shows the average variation in short-circuit current per millimetre of backsheet, along with the standard deviations. It was assumed that the current variation is proportional to the separation between the cells [10].

The experimentally determined increment in short-circuit current with distance between cells is larger than the estimated value: this may be due to multiple internal reflections of light in the PV module, which have not been taken into account in the theoretical model. The effect is greater in backsheets with a higher global reflectance.

When only high-reflectance backsheets are used, and mini-modules processed with the highest and lowest specular components are compared, the average variation in current is in the range of 0.11% abs. per millimetre of separation between the cells. The experimental power variation in a PV module with cells spaced 2mm is therefore 0.22% abs. In other words, for backsheets with similar global reflectances, the angular response of the reflected light is responsible for a power variation of 0.22% abs. If a comparison is made between backsheets with high and low reflectances, the power variation works out to be 0.27% abs. per millimetre of distance between the cells: for a standard module, this implies a power variation of 0.54% abs.

"For backsheets with similar global reflectances, the angular response of the reflected light is responsible for a power variation of 0.22% abs."

These results were used to calculate the efficiency variation in a standard industrial PV module with a separation of 2mm between cells. Comparing backsheets with high reflectances, but one having a high specular component and the second a low one, the efficiency increase of the latter is 0.22% rel. Moreover, if backsheets with different global reflectances are compared, the efficiency variation increases to 0.54% rel. in favour of the PV module processed with a high-reflectance backsheet.

Economic analysis

The impact of the optical behaviour of backsheets on the cost variations of a PV module was estimated from the results of the experiments; for this analysis the price of all the backsheets was considered to be the same. As a starting point, a PV module with 60 multicrystalline silicon solar cells and a power of 250W measured under STC was considered. The reference module price was $0.64/Wp [11].

When backsheets with similar global reflectances are considered, 0.14¢/Wp can be saved by reducing the specular component of the reflected light. This equates to an annual saving of $84 thousand per year for a 60MW manufacturing plant. However, a reduction of 0.34¢/Wp can be obtained by using a high-reflectance backsheet rather than a low-reflectance one, equating to an annual saving of around $206 thousand for a 60MW manufacturing plant.

Besides the module efficiency improvements, these results demonstrate the importance of backsheets in potentially reducing price per Wp, resulting in cost savings at an industrial plant.

Conclusions

The results of a study of backsheet optical properties and their influence on PV module efficiency, cell-to-module losses and price per watt have been presented. It is usually assumed that the reflection from the backsheet is approximately Lambertian, but this is not always the case. It was demonstrated that, as well as global reflectance, the angular response of the light reflected in the backsheet has a significant influence on the short-circuit current of a PV module.

A total of 33 backsheets formed of fluoropolymer and/or non-fluoropolymers layers was analysed. In spite of the variation found between different backsheets, white EVA films in general demonstrate the highest global reflectance, while backsheets with white EVA and fluoropolymeric layers yield the best angular response.

When backsheets with similar global reflectances are considered, theoretical studies indicate a power increase of 0.10% per millimetre of separation between cells in the PV module as a result of using a backsheet having a low specular component compared with a backsheet having a high specular component. Moreover, the difference is 0.18%/mm if a high-reflectance backsheet is used instead of a low-reflectance one. An experimental study determined those differences to be 0.11%/mm and 0.27%/mm respectively. Variations between theoretical and experimental study results may be due to the presence of multiple internal reflections of the light reflected in the backsheet.

"An improvement in efficiency of 0.22% rel. can be achieved in a standard PV module with the use of a backsheet having a low specular reflectance"

The efficiency of a PV module is influenced by the backsheet. In this respect, and for backsheets with similar global reflectances, an improvement in efficiency of 0.22% rel. can be achieved in a standard PV module with the use of a backsheet having a low specular reflectance compared with another having a high specular component. The efficiency improvement rises to 0.54% rel. if a backsheet with a high global reflectance is used rather than one with a low reflectance.

If the price of the backsheet is assumed constant, the use of one with a low specular component yields a reduction of 0.14¢/Wp compared with another having a high specular reflectance. If backsheets with high and low global reflectances are compared, the variation in the price per Wp is 0.34¢. These values represent, respectively, a saving of around $84 thousand/year and $206 thousand/year for a 60MW manufacturing plant.

Acknowledgements

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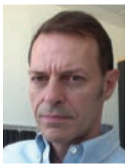
About the Authors

Salvador Ponce-Alcántara has a master's in electronic engineering from the University of Granada, and received his Ph.D. from the Solar Cell Institute of the Polytechnic University of Madrid (UPM). Since 2007 he has worked in the R&D departments of different companies (Pevafersa, Isofotón) on the optimization of fabrication process steps for high-efficiency crystalline silicon solar cells and PV modules. He joined the Valencia Nanophotonics Technology Center (NTC) at UPV in 2011 as head of the PV module section.

Alberto A. Vivas Arangú has a diploma degree in electronics engineering from the Polytechnic University of Antonio José de Sucre in Venezuela. He received a master's in system integration and corporative networks from the Polytechnic University of Valencia (UPV), Spain. In 2014 he participated in an R&D project developed at the Valencia Nanophotonics Technology Center at UPV that concerned an optical study of photovoltaic backsheets in order to improve the power of solar modules.



Guillermo Sánchez Plaza is a co-founder of the Valencia Nanophotonics Technology Center at UPV, where he is currently the Director of Technology. He began research in the PV area in 2009 and has extensive experience in nanomanufacturing processes for optoelectronic devices, on both industrial and laboratory scales.

Enquiries

Dr. Salvador Ponce-Alcántara
Valencia Nanophotonics Technology Center
Polytechnic University of Valencia
Building 8F, Camino de Vera s/n
46022 Valencia, Spain

Tel: +34 96 387 70 00 (Ext. 88101)
Email: salponce@ntc.upv.es

Production monitoring in PV: Principles, methodology and deployment

Thibaut Lemoine, STS-Certified, Kunshan, China

ABSTRACT

With lower returns on investment in PV projects, financial institutions have an ever-increasing demand for risk mitigation. Project stakeholders are asked to provide evidence of risk-management actions and have to look for ways to guarantee an adequate level of quality for their systems. Product certification, although necessary to help qualify the design of a product, does not provide a guarantee that mass production will achieve the targeted quality level; it has therefore become necessary to find reliable methods to assess the quality of PV systems on a large scale. Production monitoring, as part of a global quality plan for a PV system, is a cost-effective way to implement real-time checks in the manufacturing facilities, providing reassurance for stakeholders and helping manufacturers to improve their manufacturing processes. This paper details the principles behind production monitoring, the methodology used and how to deploy a production-monitoring project.

Introduction

When asked about his method to improve efficiency in workshops, Toyota Production System guru Taiichi Ohno used to reply that he had two methods: his legs and his eyes. From this concept was derived a principle called *Genchi Genbustsu*, which could be translated as 'go and see'. The principle is based on the fact that to truly understand what happens in workshops, you have to go there, where the work is actually performed. The gemba – 'the real place' – is where you are able to see and understand the problems and, from there, solve them.

This approach also highlights two ideas:

1. No matter how much reporting is fed back to the management or external stakeholders, it is always, by definition, an incomplete and subjective representation of reality, and measurements will only reflect part of what is actually going on in the workshop.

2. By being in the workshop, you increase the chances of your observing problems while they occur and hence of their being dealt with right away.

Production monitoring is just about that: go and see!

The need for production monitoring

Most PV products are nowadays certified by reputable certification organizations; however, end users, EPC and project developers still face quality issues when they receive their products or during the life cycle of their PV systems. The reason is that stakeholders often rely solely on certification of products, which, although necessary, is not sufficient to guarantee the expected performance and reliability of the products and, as a consequence, the return on investment (ROI) of a project.

In order to appreciate the problem, a better understanding of the certification process of products is necessary. Standards are issued by different organizations, whether they be the International Electrotechnical Commission (IEC), Underwriters Laboratories (UL), or independent laboratories developing specific test protocols focusing on long-term reliability. All these standards have the same purpose: the *qualification of a design* by a manufacturer to sustain the conditions described in the standard and to achieve the target performance over time.

The principle behind these standards is to say that once the design of the product (its components and construction) is validated, the factory will manufacture products that are identical to the qualified design, guaranteeing the desired performance and reliability. And this is where the problem lies.

> "The main issue is to know how representative of future production the specimens tested by the laboratory are."

Representative samples and consistency of the quality level

In order to reduce certification time and make certification affordable to the manufacturers, the certification organizations perform tests on only a few samples (8–10 samples per family of products); moreover, for practical reasons, none of the samples will actually go through the whole series of tests described in the standards. The standards imply that if the specimens tested during certification comply with the requirements set in the standard, then all the products made by the manufacturer will also comply with those requirements. This works if all the products made in mass production are actually identical to the specimens tested.

But the main issue is to know how representative of future production the specimens tested by the laboratory are. Although these samples are supposed to be taken randomly from the production line and sent to the laboratory for testing, manufacturers actually select them very carefully in order to avoid rejection during testing. After the samples have been carefully chosen, they undergo a series of additional tests that the 'normal products' will not be subjected to. The specimens are therefore not representative of what will come out of the production line.

The second issue is related to the stability of the manufacturing processes and the consistency of the level of quality of the products. A lot of things can go wrong during mass production, especially with ever-increasingly complex manufacturing processes and extensive manual labour.

In order to compensate for the lack of

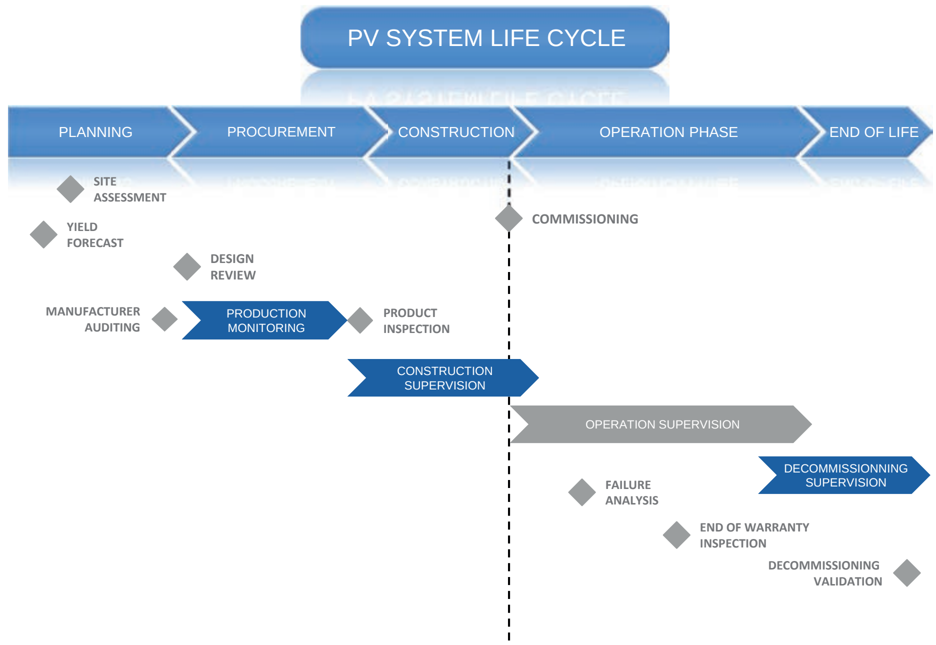


Figure 1. Integration of production monitoring in the PV system life cycle.

requirements set out in the standards regarding factory operations, most of the certification organizations have introduced stricter requirements in their own certification processes, such as an initial audit of the factory and regular visits to the manufacturing sites during the period covered by the certification. However, audits and visits work as a snapshot of the factory on a specific day and do not necessarily represent the 'normal' activity of the factory on any given day, because these audits are planned in advance and the factory will make sure that there are no issues on the day of the audit. It then follows that, in order to ensure the right quality level of a specific order or project, it is of the utmost importance to be onsite when the production will actually run. That said, the question is what to check, how and when.

Production monitoring can be implemented at different stages of the relationship between a manufacturer and its customer. Although considered at the time of production for a specific project, production monitoring can be a very useful tool at the supplier selection stage for manufacturers' clients for assessing the ability of a particular manufacturer to produce quality products on a large scale. Since the monitoring process will run over an extended period of time, it complements the initial audit, which will be limited in terms of gaining an understanding of the production capabilities (Fig. 1). This is particularly adapted to distributors or developers of residential systems who intend to establish a regular cooperation with manufacturers with repeated orders over time. In such cases, production monitoring will first occur during a trial order, allowing the client to make sure that future productions will not be affected by epidemic failures or be delayed at critical stages of the project deployment.

In some cases, third parties are directly required by some proactive manufacturers to either provide reassurances to the manufacturer's clients about the quality level of the products they deliver or provide an external eye on the manufacturing processes with the purpose of continuous improvement and upgrading to world-class manufacturing.

Principles of production monitoring

The first principle of production monitoring is that this activity is related to one specific batch of production, covering either a small order or an entire multi-megawatt project. The activities will be implemented either on the whole quantity or by sampling, but only on the batch(es) of production related to the project.

Although production monitoring usually refers to the production of PV modules, it can actually be deployed under different names in order to cover not only all the components of a PV system, such as inverters, structure and other components, but also the construction of the system itself. In the latter case, production monitoring is often referred to as *construction supervision*, which focuses on all construction activities and processes as well as on the components necessary to obtain a final product, namely the PV system.

Production monitoring can also be performed on subcomponents of the PV modules, such as cells, wafers and ingots. For the purpose of simplification, the focus in this paper will just be on the PV modules, but the deployment of a production-monitoring project can easily be translated to the above-mentioned components and different stages of the system deployment.

Production monitoring can thus take different forms and present a scope that can be extended or reduced according to specific needs and agreement between the manufacturer and the client. It is therefore imperative to clearly define the objectives and the scope of the activities, as well as the extent and the boundaries of those activities, such as the physical locations, including the period of time covered by the activities.

In order to obtain a final product with the expected level of quality, there are essentially two aspects in question: use the right components and implement adequate manufacturing processes to combine these components. Production monitoring will focus on these two items to ensure that the targeted quality level is achieved.

Using the right components

The right components can be understood to be the ones approved by the certification body during the

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certification of the product and/or the ones agreed between the manufacturer and the buyer. The list of components used for a specific product is grouped in a bill of materials (BoM) – a document which will be part of the supply agreement between the manufacturer and the customer.

Components can be used either as single-source components – meaning that there is only one model of a specific component and only one manufacturer allowed to build the final product – or as multi-source components. In the latter case, it is imperative to know what combination(s) of components are allowed.

Because of logistic issues, costs, or other supply chain concerns, manufacturers will make use of different combinations of components to build the final products for different orders without always carefully considering the compatibility between these components. As a consequence, in a multi-source components environment, final products can be very different from one production lot to another. One observed relevant example of this is the case of a manufacturer which found out, at its own expense, that a certain EVA material was not compatible with a particular backsheet, which resulted in delamination problems in its modules, amounting to several megawatts of wasted products.

To address the issue, over the past few years certification organizations have developed in their test reports some compatibility tables that specify which combinations of components have been tested and then approved for use.

Figure 2. Incorrect handling during a junction box sealing operation.

Production monitoring will focus on the use of these combinations of products in particular.

Implementing the necessary processes

It has been noted that the choice of components and their combination can have dramatic consequences on the quality of the final product, but the manner of combining these components is no less crucial. In a similar way to that for the components, the first focus of production monitoring in assessing the manufacturing processes is to ensure that the manufacturer uses the approved facilities to perform the manufacturing operations. Once again, 'approved' can be understood to denote either that the facilities have been approved by a certification body, or that a client has specifically requested that, for instance, the products be manufactured on a specific line or in a designated workshop.

With the spectacular development of production capabilities (especially in China), and recent mergers and acquisitions, manufacturers sometimes run several factories and workshops that differ significantly in terms of levels of quality. In the history of the development of their companies, manufacturers have strengthened their processes by investing in newer and better-performing equipment; this is usually done without relinquishing the older production lines, which creates large disparities in terms of processing capabilities, even within a given workshop. It is not unusual to have fully automated production lines populated with robots operating next to production lines supported by an army of workers performing manual soldering operations and transporting semi-finished products in utterly non-recommendable ways (Fig. 2). Some clients are occasionally lured into having so-called 'certified' products made in a factory that was actually never audited by the certification company.

Because products are usually certified with respect to a factory as a whole regardless of the discrepancies in the processing capabilities of different production lines, it is strongly recommended that buyers take into consideration the workshop in which (or even the production line on which) their products will be manufactured.

Quality control plan as the manufacturing processes map

Once the facilities have been identified, the proper assessment can begin. Just as for any type of work, the team in charge of assessing the processes will need a map: this map is called a *quality control plan* or *QCP*.

A QCP is both a document and a strategy, usually presented in the form of a list or table that sets down all the processes and describes the limits within which the processes are to operate. It sets the pre-established disposition (PED) that is necessary in order to master all the manufacturing activities for a product, or a range of products, identifying the parameters impacting the quality of the final products as well as the characteristics of the products under surveillance. The QCP covers all the processes of a manufacturing site, from reception of components to delivery of final products to the customer (Fig. 3).

The QCP itemizes not only the manufacturing processes that add value to the products (manufacturing operations) but also all necessary operations for producing the final product, such as the quality controls performed on the semi-finished products, whether on the production line on all the products or off the production line in laboratories. The plan will also list all operations pertaining to the transportation of components and subassemblies along with the related storage aspects.

The QCP is divided into different sections, each identifying various elements of control activities. For each of the processes, a first field will contain a process description, including the type of process and the equipment used. A second field will pinpoint the characteristics of the process (characteristics of the product itself and of the process) which represent the input variables that must be controlled in order to minimize the variations in quality. A third part will identify how, when and to what extent these characteristics will be controlled, as well as the method used to perform the controls, including the related documentation. In the final field, a contingency plan

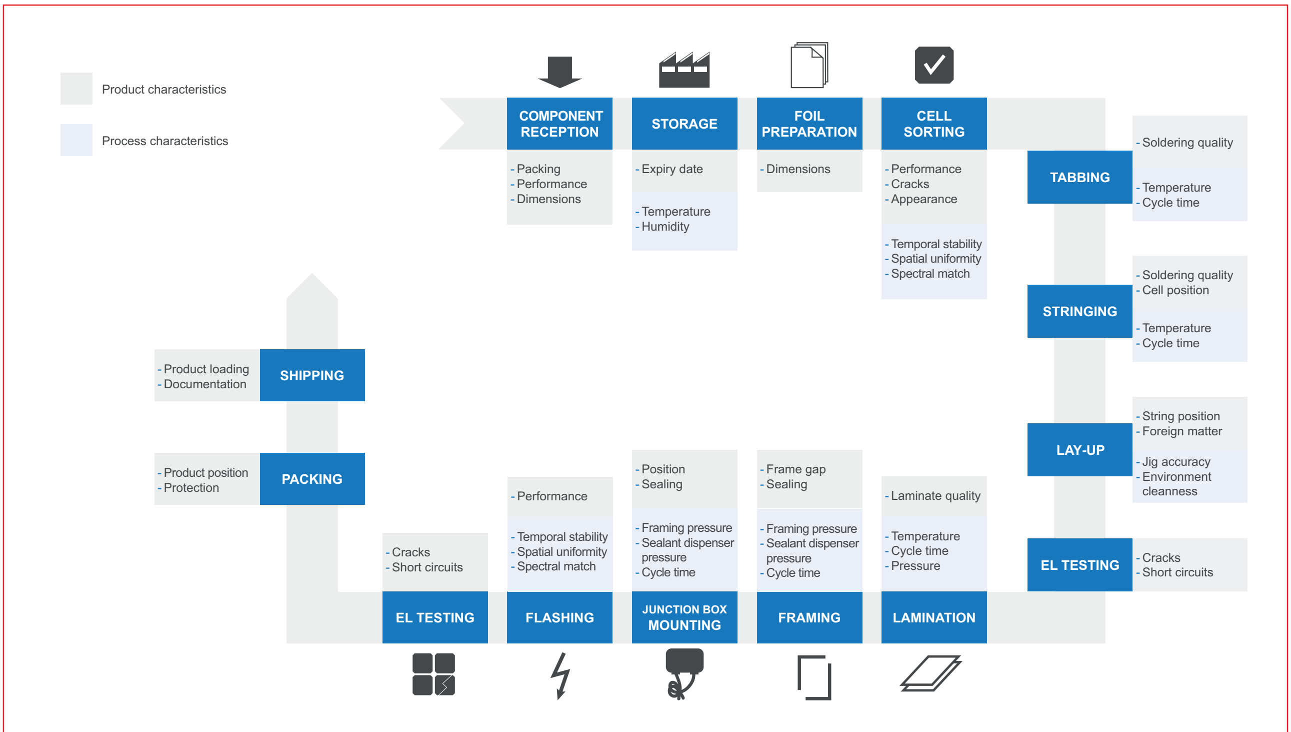

Figure 3. Simplified graphical representation of a quality control plan.

will detail what actions are to be taken if the measured characteristics fall outside the limits set in the control plan.

> "The QCP will be the basis for the team performing the production-monitoring activities."

5M method to cover all aspects of the processes

As explained above, the QCP will be the basis for the team performing the production-monitoring activities. Inspectors will follow the control plan step by step and oversee the correct implementation of the QCP in the factory.

In order to cover all aspects, inspectors will focus on the 5M method, described as follows. For each step of the control plan defined above, inspectors will check that the different points of specification are actually adhered to in accordance with five criteria:

1. **Machine**: check that the proper equipment is used for the process, as well as the general condition of the equipment.
2. **Material**: check that the correct components are used, as well as the general condition of the components, including indirect materials.
3. **Method**: check that the methods defined for implementing the process guarantee that the specified characteristics will be respected.
4. **Manpower**: check that the operators participating in the process are qualified to perform their duties and respect the instructions set for the process.
5. **Milieu**: check that the environment allows a proper implementation of the process (tidiness, cleanness, temperature, humidity, etc.).

Deployment of a production-monitoring project

In the case where the main activities of production monitoring occur during actual production in the factory, specific steps have to be followed before and after these activities in order to successfully deploy a production-monitoring project.

Preparation

As with any project, the first task is to prepare the production monitoring. This part will be done in cooperation with the project client, be they a buyer, a manufacturer or a third party. At this stage, the objectives, scope and criteria for the project will be defined. The objectives will specify what is to be accomplished during production monitoring and may include the release of a production batch, the beginning or resumption of production activities, or the identification of areas for potential improvements in product manufacturing.

Typical information will include the quantity of products that will be subject to monitoring, and the sampling plan clarifying whether all the production or only a certain percentage is to be monitored, along with the rules for increasing or decreasing this percentage. Another point to be agreed upon will be the authority provided to the monitoring team allowing them to halt or continue production according to their findings during monitoring activities, as well as under what circumstances they are permitted to act.

Technical information is collected in order to plan the monitoring duration, assign the resources needed for the project and prepare the working documents. Typical technical information includes product specifications, BoMs, factory information, equipment lists, production information, production plans and quality control plans. In some cases, not all of the documentation may be available prior to the audit activities: part of the preparation activities will therefore be performed onsite, which can impact the duration of the onsite activities.

A review of all the information is performed to analyse the needs, and the onsite inspection team is appointed to assess compliance with the scope, objectives and criteria of the project. The resources will be allocated with regard to workforce size and technical knowledge necessary to perform the job. Once the preparation task has been completed, an announcement is made to the different parties in order to clarify the work to be done and to facilitate the onsite activities.

Onsite activities

The first task of the workforce conducting the onsite activities is to hold an initial meeting with the manufacturer's management team, as well as with those responsible for the processes that will be monitored. The purpose of this meeting is to confirm the scope of the production-monitoring project, to present a short summary of how the activities will be undertaken, to verify the communication channels and to provide an opportunity for the manufacturer to ask questions. In effect, the opening meeting will introduce the participants, confirm the timetable, ensure that the resources needed by the inspection team are available, and provide clarification on factory safety rules and the methods used as well as on confidentiality issues.

Depending on the complexity of the project, intermediate formal meetings may be arranged on a regular basis with the manufacturer either with or without the organization in charge of the project. In a general manner, the team leader will communicate how the work is progressing, and any evidence of an immediate and significant risk will be reported immediately to the project client.

As discussed earlier, the team will then move onsite and act in accordance with the 5M work methods by collecting information, including records, interviews with personnel, observations and the results of witnessing the work performed in the facilities. The information is then verified and evaluated against the agreed criteria in order to report and, if necessary, to take immediate action. The easiest way to perform the activities is to follow the control plan from reception of components to shipping of final products to customers.

Project conclusions

Prior to a closing meeting, the team confers in order to review the findings of the onsite activities, to agree on the conclusions and to prepare recommendations, if specified by the project objectives.

A closing meeting is then held by the inspection team to present the findings, so that they are understood and acknowledged by the manufacturer, and to agree, if relevant, on the presentation of a corrective and preventive action plan.

Reporting

The audit report provides, as far as possible, a complete, accurate and concise record of the activities performed, including or referring to the project objective, scope and criteria, the period covered, the findings and the conclusions. The report, in the case of complex or numerous processes, details the observations and findings for each of the different processes within the scope of the work. It also lists the areas that were not covered by the activities of the team. If it is specified within the scope of the project, the report also includes recommendations for improvements as well as a relevant action plan related to the findings.

The report is reviewed and approved and then distributed within a previously arranged time frame to the agreed recipients. In certain cases, the activities may be complemented by a follow-up in order to verify that some agreed actions have been implemented and are effective.

In-house or third-party production monitoring

When faced with the need for production monitoring, project stakeholders are confronted with the decision whether to perform these activities in-house or to entrust them to third-party organizations to perform on their behalf. Different factors may influence this decision.

Depending on whether the need is an external or internal choice, the decision may be restricted. Some project stakeholders, especially financial institutions, sometimes require that approved organizations be called in to perform the work. This provides the guarantee to these stakeholders that the work will be performed by an impartial and skilled workforce using indisputable methods. Manufacturers too may require that work be performed by these organizations for reasons of impartiality.

Another factor influencing the decision is cost. Where organizations might think that it would be more cost competitive to perform such work in-house, they are usually faced with unplanned costs which, ultimately, make it much more expensive than if they contracted specialized firms to perform the job. Indeed, if a project grows in size, the need for resources within the inspection team can rapidly expand, and with them the related cost. Manufacturers are not necessarily located close to the buyers, and the transportation and accommodation costs alone can make it already a burden for the stakeholders if they decide to perform the job themselves.

Another economic concern relates to making the best use of the resources needed to perform the work. As discussed above, production-monitoring activities are extremely technical activities and require both excellent general knowledge and process expertise. This means that the organizations intending to perform production monitoring in-house will have to recruit skilled labour, but with a workload factor that can be dramatically low, which increases costs even more.

If an organization decides to contract a third-party partner to perform the job, the next decision will be choosing the right one. Even if there seem to be many companies providing this kind of function, only a few of them will be able to guarantee the professional level of service required to ensure the requisite level of quality of the products delivered. Some companies providing this type of service cover a wide range of products and are not specialized in the PV industry. Although these companies have usually developed solid methodology for performing the activities, most of the time they lack the technical expertise in manufacturing processes that is necessary for identifying the risks to the products; moreover, they may not have the ability to judge if the PEDs are exhaustive and relevant to manage the risk. Even within the PV industry, some companies will focus primarily on the production of PV modules, while others will focus on the downstream part of the project, mainly on construction supervision and commissioning. Depending on the size of the project under consideration, other companies might have trouble providing enough resources to cover the whole production, with a consequent decrease in the level of service provided.

It is therefore important to be able to assess the capabilities of these third-party companies in terms of technical capabilities (by understanding the level of skill of the team assigned to perform the work) as well as in terms of availability of resources allocated to a project. Previous-project references/endorsements, inspector profiles and accreditation by a recognized accreditation body can provide a good indication of these factors.

> "Monitoring activities have to be performed in a professional way with a high degree of expertise to guarantee the outcome of the work."

Conclusions

While production monitoring provides a cost-effective way to mitigate quality-related risks for a project, the monitoring activities have to be performed in a professional manner with a high degree of expertise to guarantee the outcome of the work. The results achieved will largely depend on the resources allocated to the project and on how rigorous the monitoring methods used will be. It is therefore essential to assign the work to the right team either internally or externally.

The principle of production monitoring is not the replacement of the controls performed by the manufacturers but rather ensuring that these controls are performed correctly. Production monitoring does not relieve the manufacturers of their responsibilities, and the ultimate success of a project will still be closely related to the choice of the right partner.

Despite paying the most careful attention during production monitoring at the different critical steps of the production, an inspection team cannot be everywhere at the same time, and it is possible for the team to miss some issues. The teams do their utmost in performing the job to the best of their ability; however, as for any onsite activity, they are very reliant on the cooperation of the manufacturers and on the availability of equipment onsite. It is therefore recommended to include other means of control – such as off-site inspections and tests by sampling – in order to minimize the uncertainty related to the quality risk. In any case, production monitoring remains one of the most efficient ways to increase the overall quality levels of products installed worldwide and is a useful tool in the great adventure of making PV one of the major sources of energy for the future.

About the Author

Thibaut Lemoine is a co-founder and the general manager of Senergy Testing Solutions Ltd (STS), a company that is involved in the creation and implementation of individual product certification in the PV industry. He has an extensive knowledge of PV manufacturing in China, where he has been working for almost 15 years in various industries, including PV. Thibault received a master's degree in mechanical engineering from the National Engineering University of Belfort, France, and a master's degree in international industrial business management from the Technical University of Belfort-Montbéliard.

Enquiries

STS-Certified
777 Yuyang Road
Gaoxin District, Kunshan
Jiangsu Province
215300 China

Tel: +86-21 63816578
Email:
alexander.minuzzo@sts-certified.com
Website: www.sts-certified.com

Fab & Facilities

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Market Watch

Adapting conventional tabbing–stringing technology for back-contact solar cells and modules

Tom Borgers[1], Jonathan Govaerts[1], Arvid van der Heide[2], Stefan Dewallef[2], Ivan Gordon[1], Jozef Szlufcik[1] & Jef Poortmans[1]

[1]imec, Leuven; [2]Soltech, Tienen, Belgium

ABSTRACT

In anticipation of the expected increase in the use of back-contact cells in future PV modules, a number of different concepts have been proposed. This paper focuses on one approach that aims to stay close to conventional solder-based technology (tabbing–stringing) while still allowing the use of back-contact cells (which have more complex back-side metallization schemes). The advantages and disadvantages of such an approach are discussed, and the development of this technology is described in terms of process flow, materials, characterization and reliability.

Introduction

The current standard technique for manufacturing crystalline Si PV modules is based on two-side-contacted cells and has been widely adopted. The method consists of first interconnecting the separate cells into strings by soldering ribbons from the front of one cell's contacts (tabbing) to the contacts on the back of the neighbouring cell (stringing). The strings are then interconnected and laminated between a transparent glass or polymer front sheet and a glass, metal or polymer back sheet using an encapsulation material, the most common being the cross-linking material ethylene-vinyl acetate (EVA).

However, with the drive towards higher efficiencies, several different concepts for silicon back-contact solar cells have been proposed, investigated and developed. Well-known back-contact cell concepts include the emitter wrap-through (EWT) and the metallization wrap-through (MWT), which rely on cross-sectional conduction using vias in the silicon to draw the current out of the front-side active area. As an alternative concept, interdigitated back-contact (IBC) cells have both polarities at the back through an interdigitated grid.

All back-contacted cell concepts aim to avoid optical shadowing effects by reducing the front-side metallization. For each type of cell, different layouts have been developed, resulting in various module interconnection and integration flows [1]. It is important to note that since all cell contacts are on the same side, there is an increased risk of shunting during interconnection when the second-level (interconnection) metallization is applied. To avoid shunting, alignment is more critical, and (whenever the interconnection metallization has to cross the metallization with opposite polarity on the back side of the cell) an additional insulating layer is essential.

> "To avoid shunting, alignment is more critical, and an additional insulating layer is essential."

MWT interconnection methods

A method for fabricating modules with MWT cells is discussed in this paper.

For these types of cell, two main groups of module interconnection flows are currently in competition: 1) technologies based on the use of integrated backsheets; and 2) interconnection schemes much more closely related to conventional module (stringing) technology as described earlier.

Both schemes allow a larger cross section of conductors between cells, resulting in lower efficiency losses at the module level. For both groups, the use of an insulating layer between the connectors and the metallized back side of the cell is needed to avoid shunting cells. In practice this suggests the use of an insulating layer with holes that must be positioned over the back side of the cell in such a way that they face

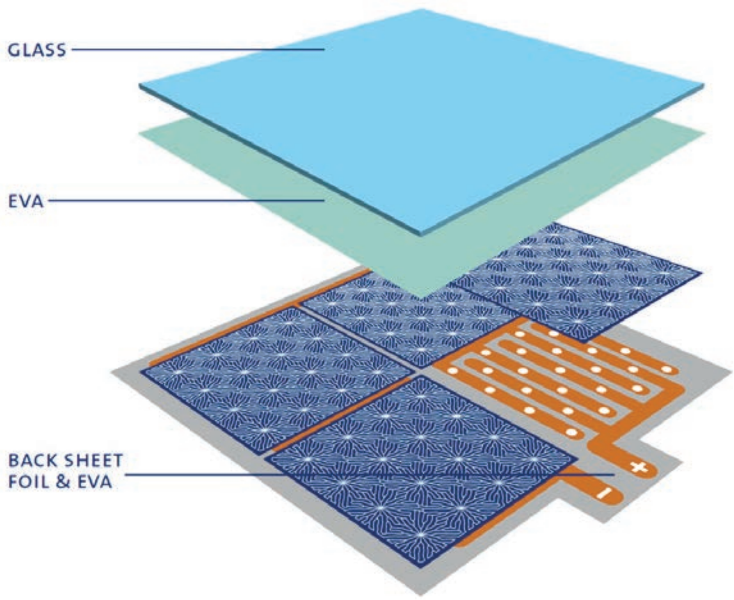

Figure 1. Schematic expanded view of the integrated backsheet approach.

the contact points of both polarities in order to allow electrical connection to the second-level (module-level) interconnection metallization. The making of the holes and the alignment of the insulating layer are two operations.

In the case of the first group, based on integrated backsheet approaches, all current flows through a patterned laminated copper foil with integrated electrical circuitry, which also incorporates the laminate films required at the back side of the module to protect the strings inside from the environment. The typical build-up of such technologies is shown in Fig. 1 [2]. Of interest in this group of technologies is the limited cell-level handling and process steps, as both lamination and interconnection of the cells could take place during the same step. Moreover, only one alignment step is necessary to align the backsheet with conductors to the cells. On the downside, dysfunctional cells or cell strings cannot be measured or replaced after interconnection, owing to the integrated approach of lamination and interconnection. The integrated backsheet also has a more complex build-up than that of a standard backsheet (in that it requires patterning and alignment of conducting and insulating layers), which leads to higher costs. Both (low-temperature) conductive adhesives and solders can be used for electrical connection of the cells with the integrated backsheet.

With the second group, consisting of interconnection schemes similar to conventional stringing approaches, separate MWT cells are first interconnected with ribbons into strings by soldering, ensuring that insulation is present between cell metallization and ribbons wherever shunting might be an issue. This insulation layer can be applied to the cells as part of the cell process by incorporating a dielectric at the cell level, or by laying up an insulating sheet [3]; in either case, a patterning and alignment operation is required. The stringing is then followed by a lay-up step, in which all strings are aligned and interconnected with end (bussing) ribbons. Since the strings are electrically connected before module lamination, defective strings can be traced and repaired or replaced, reducing yield losses after lamination. On the downside, these technologies, of course, require more cell-level handling, increasing the risk of cell breakage, especially in view of the trend towards thinner cells.

Approach, process flow and steps

In this paper a technique belonging to the second group – i.e. based on stringing technology [4] – is investigated. For this approach, a woven glass fibre sheet is used as an insulation layer, which covers the entire area where shunting between ribbon and cell metallization might be an issue. Electrical connection is established only where conductive material penetrates the fibre sheet. This can be achieved by applying solder paste locally to the contact pads of the cell; this process then replaces the patterning and alignment operations for the insulation layer. The main difference with this technique compared with standard technology for stringing two-side contacted cells is clearly the addition of a woven glass fibre insulator. Fig. 2 schematically gives an overview of the process flow. The technology developed for this approach is described in detail in the following process steps, numbered as shown in the figure.

"The main difference with this technique compared with standard technology for stringing two-side contacted cells is the addition of a woven glass fibre insulator."

Step 1: The MWT cell (description)

MWT back-contact cells (156mm × 156mm) from Photovoltech were prepared from monocrystalline silicon wafers according to the process described in Van Kerschaver et al. [5], wherein the contact points to the two oppositely doped regions are placed on the back-side surface. As shown in Fig. 3, the back side of the cell consists of a non-solderable aluminium coating, and six rows of solderable silver contact points. The first, third and fifth rows

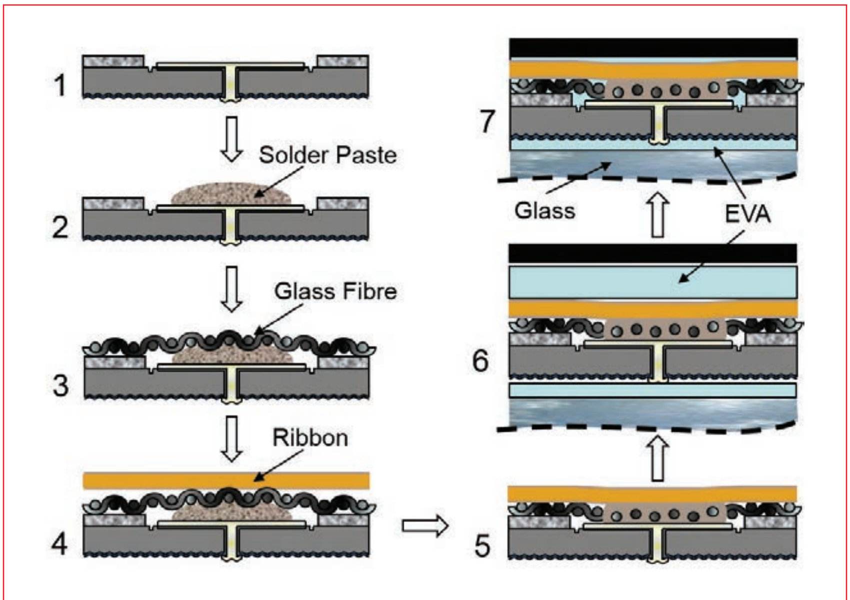

Figure 2. Schematic overview of the process flow.

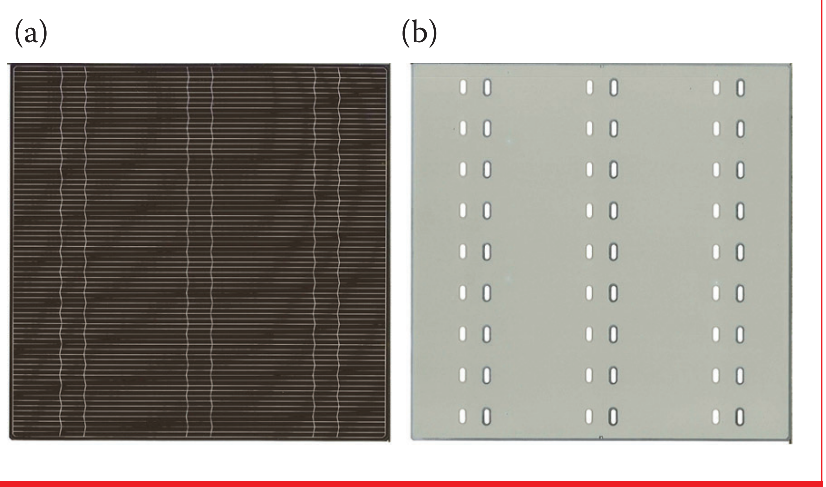

Figure 3. Front-side (a) and back-side (b) appearance of the Photovoltech MWT cells used.

(Fig. 3(b)) provide the emitter region with nine solderable contact points, connected through vias to the fingers on the front (illuminated) side and surrounded by a groove in order to be electrically isolated from the aluminium metallic layer. The second, fourth and sixth rows are solderable contact points for the back-side base region.

Step 2: Solder paste dispensing

Drops of solder paste are deposited on all cell contact points by fluid dispensing. The solder paste consists of a no-clean (NC) flux basis containing Sn/Pb/Ag alloy powder; this was selected because of its versatility in soldering to the alloy covering the connectors and its resistance to the later step of EVA lamination. The amount of solder paste is adjusted according to the thickness of the insulating layer which will be applied in the next step.

Step 3: Laying a uniform layer of insulating fabric material

A uniform layer of woven electrically insulating fibres is applied to the back side of all the cell strings, each consisting of 11 cells. The plain weave fabric with a black finish is texturized, and no special openings are made in the fabric after its manufacture. In order to cover the connectors in the space between the cells for aesthetic reasons, the fabric weaving is denser outside the cell area. The fabric covers the entire surface of the cells and is made of glass fibre material. No alignment of the fabric is necessary, since no pattern with openings is created for placing on each contact point. The material is resistant to the temperature required for soldering as well as for the later lamination (encapsulation) step. Examples of such a fabric are shown in Fig. 4.

As this insulator is the main differentiator of this technology from standard tabbing–stringing technology in terms of materials, the choice of woven glass fibre for the insulating fabric material will be examined in greater detail. First, it is already used for various purposes in solar panels and exhibits excellent physical properties that will contribute to the dimensional stability and reinforcement of the modules. Furthermore, woven glass fibre has excellent electrical insulation chemical properties, being essentially inert (moisture-resistant, no outgassing) and fire-resistant. Finally, and rather importantly, depending on the type of glass fibre fabric, it can be relatively inexpensive.

Several basic variables must be considered when selecting a woven glass fabric. Different glass compositions are available; for the purpose in hand, E-grade glass is preferred. Yarns are composed of continuous filaments, which guarantees a constant quality and thickness of the weave. The average filament diameter and the strand count can be chosen within a certain range; these variables will partly determine the total thickness of the weave.

For this application, a plain weave pattern is used. The fabric density differs outside the cell area: it is lower to save on fabric material where it is not needed, and higher to provide some covering of the connectors in the spaces between the cells, which prevents unwanted reflection of the sunlight by the connectors and contributes to the aesthetic appearance of the module.

Woven glass fibre fabric can be used with no finish; however, when larger openings are desired, it is useful to have some weave lock applied to the fibres to improve dimensional stability. The weave-lock material is selected for its chemical compatibility and for its ability to guarantee sufficient adhesion with the EVA encapsulating material used in the preparation of the solar panels. The mesh openings in the insulating layer are small with respect to the size of the contact points and of the ribbon connectors, but large enough for the solder to flow through

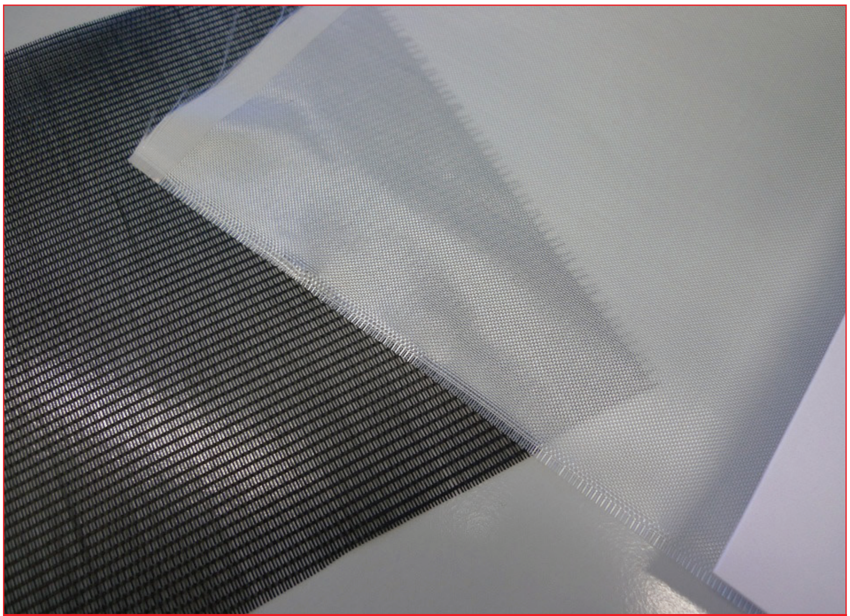

Figure 4. Examples of woven glass fibre fabric material (black version left, white version right) which can be used for the insulating layer.

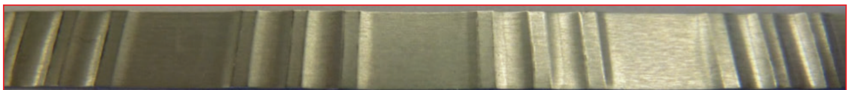

Figure 5. Wide copper ribbons with preformed expansion bends.

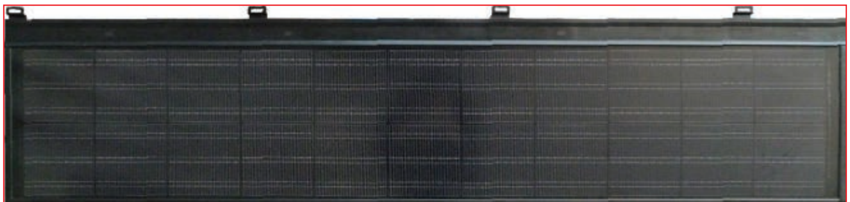

Figure 6. Photograph of the resulting modules.

	I_{sc} [A]	V_{oc} [V]	FF [%]	P_{mpp} [W]
Cells (class 1800 data)	9.21	0.62	76.8	4.41
Module average (of 8)	8.75	13.76	76.4	91.91
Best module	8.79	13.80	76.8	92.60

Table 1. Performance of the resulting modules.

the openings. The colour of the weave lock is also customized to produce a uniform appearance of the module after lamination. The glass fibre can be texturized to give it a denser and even more uniform appearance.

Step 4: Alignment of ribbons

The connectors are standard solderable ribbons, consisting of 80µm-thick and 6mm-wide strips of copper covered with a thin (9µm) coating of tin–silver solder to ensure optimal soldering. Expansion bends, as illustrated in Fig. 5, are preformed on the ribbons for relieving stress on the cells after the soldering step. The tinned copper ribbon connectors are aligned over each of the six rows of contact points, spatially separated by the fabric material from the back-side surface including the contact points.

Step 5: Soldering

The cells are heated in a semi-automatic solder tool with adapted solder heads, and an automatic contact soldering process is then applied on top of each contact point with light pressure to ensure good contact between the layers. Local pressure on each solder point is distributed by the ribbon and the underlying glass fibre tissue, thereby protecting the cell.

During this step, the solder paste melts and passes through the mesh openings in the woven fabric, while the connector and the contact points remain spatially separated by the fabric; this results in an electrical connection that penetrates the fabric only in those locations where solder paste was present. In places where no solder paste has been applied and a soldering step took place, the fabric will serve as an insulating material and as a spacer, thus preventing shunts and undesired electrical and mechanical connections, and remaining physically unaffected.

The temperature is set to avoid any melting of the solder on the connectors, but sufficiently high to promote melting and reflowing of the solder paste; this is possible since the ribbon's solder coating possesses a higher melting temperature than that of the solder paste because of the absence of Pb in the alloy. Since surface tension (and adhesion) of the solder on silicon and aluminium is very low, possible solder drop spills that would partly extend the silver contact pads retract within the confines of the silver contact pads, resulting in a self-alignment process and thus a reduced risk of shunts.

Step 6: Lay-up and interconnection of strings

Eleven identical cells are connected in series as described in the previous steps to form a string. The modules prepared here each consist of two strings. After these strings have been prepared, they are placed on the front-side EVA-lined solar-grade glass of a solar panel, and the individual strings are connected with end (bussing) ribbons. To finish the lay-up, the rear-side EVA encapsulant sheet and protective black back-side foil are then put in position. These two sheets have two punched holes to allow feed-through of the interconnectors to the junction box. This step is similar to a traditional lay-up of standard cell strings made of front- and back-side contacted solar cells.

Step 7: Lamination

During the subsequent lamination of the cell strings into a solar panel, the fabric, ribbons and cells are embedded in the EVA encapsulation material. The fabric provides additional dimensional stability to the encapsulation material in addition to reinforcement of the solar panel.

Results – characterization and reliability

In total, eight single-cell modules were prepared according to the above-mentioned process flow. Preliminary electrical evaluation tests on these modules showed a loss in fill factor of about 1% compared with the standalone cell. The dense fabric outside the cell area gave a uniform black appearance to the module after lamination. All measurements on the laminated modules were carried out under standard conditions [6].

> "The connection technology provides both excellent electrical insulation and electrical conduction."

A photograph of the modules is shown in Fig. 6; the performance of the best one is presented in Table 1. Although the data for the actual cells used is not available, the cell class performance data is included to give an indication [7]. The high value of 76.8% for the fill factor demonstrates that the connection technology provides both excellent electrical insulation (so a reduction in shunt resistance is avoided) and excellent electrical conduction (the increase in series resistance is minimized).

Reliability testing was also carried out on the modules. As an example, Fig. 7 shows the evolution of power and

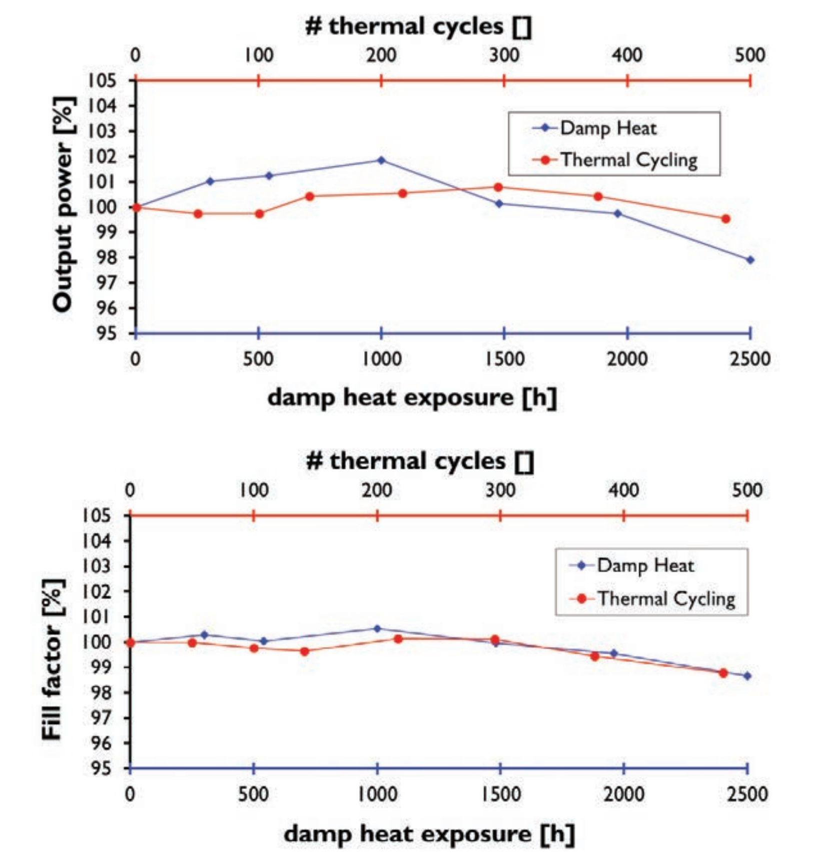

Figure 7. Evolution of power and *FF* for modules subjected to thermal cycling and damp heat.

Figure 8. Automated tabber–stringer system for back-contact cells, including paste dispensing, glass fibre fabric lay-up, hot air soldering, and EL testing of the fabricated strings.

FF of the average of two modules that were subjected to thermal cycling and of two modules that were subjected to damp-heat conditions. For reference, IEC standard testing specifies a pass/fail criterion of a drop in power of a maximum of 5% after 200 thermal cycles or after 1000 hours of damp heat.

The modules were also submitted for, and passed, full IEC certification testing [8] at Eliosys. This also indicates the promising potential of this technology in terms of the reliability aspect.

"The next step is upscaling and automation."

Conclusion and outlook

A concept for manufacturing modules from back-contact solar cells has been proposed and demonstrated. Considering the promising potential of this technology in terms of performance, cost and reliability, the next step is upscaling and automation. To this end, an automated tabber–stringer has been acquired and custom modified: the system is shown in Fig. 8. After hook-up and installation, initial testing will begin..

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About the Authors

Tom Borgers joined imec in 2000, working on III-V detector technologies and developing a flip-chip approach for megapixel infrared sensors. He switched to the field of photovoltaics in 2008, when he began working for Photovoltech. His interests lie in back-contact solar cell concepts, specifically the development of module technology. In 2012 Tom joined imec's reliability and modelling group, and currently works in the Si PV group, focusing on module interconnection technology.

Jonathan Govaerts received his Ph.D. in 2009 from Ghent University, Belgium, with a thesis topic of packaging and interconnection technology for (flexible) electronics. Since then Jonathan has been working in the Si PV group at imec, focusing on cell–module integration of silicon solar cells.

Arvid van der Heide began his PV career in 1997 at ECN, where he invented a method for mapping solar cell contact resistance. In 2005 he moved to Photovoltech, specializing in the areas of characterization, metallization and MWT cells. Arvid started at Soltech in 2013, working on the development and launch of MWT modules.

Stefan Dewallef has been working as an engineer at Soltech since 1995. His experience in PV includes dimensioning, optimisation and installation at the system level, and product development and R&D of modules.

Ivan Gordon obtained his Ph.D. in the field of novel magnetic materials from the University of Leuven in 2002. In 2003 he began working at imec, where he currently leads the Si PV group. Since 2008 Ivan has been an editor of *Solar Energy Materials and Solar Cells.*

Jozef Szlufcik received M.Sc. and Ph.D. degrees in electronic engineering from Wroclaw University of Technology in Poland. From 1981 to 1989 he worked on hybrid microcircuits and low-cost silicon solar cells at Silesian Technical University, Poland, before joining imec in 1990 as head of research in low-cost crystalline silicon solar cells. A co-founder of the solar cell manufacturer Photovoltech, he acted as their R&D and technology manager from 2003 to 2012, and is currently the PV department director and Si PV programme manager at imec. He has authored/co-authored close to a hundred articles and is inventor/co-inventor of 14 patents.

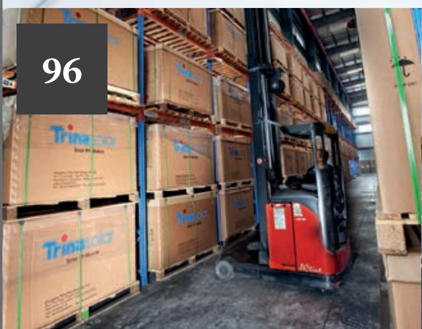
Jef Poortmans received his degree in electronic engineering from the Katholieke Universiteit of Leuven, Belgium, in 1985, and his Ph.D. in June 1993. He is the director of the Solar and Organic Technologies Department at imec, and is currently director of the SOLAR+ strategic programme, which comprises all the PV technology development activities within imec. Jef has also been a part-time professor at the Katholieke Universiteit since 2008.

Enquiries

Jonathan Govaerts
imec
Kapeldreef 75
B-3001 Leuven
Belgium

Email: jonathan.govaerts@imec.be

Market Watch



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Why p-type multi c-Si is seeing strong market-share gains
Finlay Colville, Solarbuzz, London, UK

News

Trina Solar takes 2014 top module supplier crown

The PV industry was expected to have a new 2014 market leader after both Trina Solar and Yingli Green reported third quarter financial results and given revised full-year shipment guidance, ending a battle that has raged throughout 2014 for the top spot.

The provisional winner is Trina Solar, with a shipment growth momentum of 40% minimum, compared to Yingli Green's minimum growth of only 3%, compared to 2013.

Yingli Green released third quarter results and slashed its full-year shipment guidance to be in the range of 3.30GW to 3.35GW, resulting in shipment growth of only 3% to 4.6%, compared to 2013.

Trina Solar however had guided shipments of 3.61GW to 3.66GW for 2014. Only JinkoSolar has guided (top-end) shipments over 3GW in 2014, resulting in Trina Solar becoming the leading PV manufacturer in 2014, based on fourth quarter and full-year shipment guidance.

Source: Trina Solar

Shipment growth in 2014 helped Trina Solar steal the module supplier top slot from Yingli.

World markets

'Disruptive' renewables put the squeeze on utilities

A week after German utility giant E.ON announced its withdrawal from fossil fuels and an exclusive focus on renewables, further evidence emerged that utilities face growing disruption from distributed energy technologies.

According to a study published in December by management consultancy Accenture, the growth of technologies such as PV and storage will hit utility company revenues to the tune of US$130 billion a year within a decade.

Accenture's report, 'Digitally Enabled Grid', said that by 2025 the revenues of US utilities in the US could be down by as much as US$59 billion and those in Europe by US$75 billion as their business models face a growing squeeze from distributed technologies.

Under the "perfect storm" situation modelled in the report, a worst-case scenario, utility losses could rise to as much as US$130 billion, Accenture said, though it said the most likely scenario would be losses of US$18 billion a year in the US and US$48 billion in Europe.

UN climate negotiations '15 years out of date' on renewables

World leaders negotiating global climate change policies are "10 to 15 years out of date" when discussing renewable energy technology.

CEO of the Global Wind Energy Council, Steve Sawyer, told the UN Climate Change Conference (COP20) 2014 held in Lima, Peru, in December that negotiations on renewable energy targets are a decade or more behind the advances in renewable energy.

A 100% renewable energy future is far closer than "where most negotiators at these climate talks reckon is possible", added Jeremy Leggett, representing the European Photovoltaic Industry Association (EPIA) and chair for developer SolarCentury and charity SolarAid.

Sawyer told a press conference: "A decarbonised energy system by 2050, or sooner, seems more and more likely with each passing year.

"Five years ago I would, and did say, the majority [of renewables] would come from hydro and wind power, but with the dramatic up-take in the solar industry in the last five years, and the cost reductions in that period of time, solar is already making a substantial contribution and rising faster than anyone thought it would five years ago" said Sawyer.

Leggett added that the price decrease of solar "has taken everybody by surprise, including the industry itself."

Europe news

UK solar could be subsidy-free by 2020, says German think tank

Subsidy-free solar in the UK could thrive by the end of the decade, according to a report published by Berlin-based think

Source: Lightsource Renewable Energy

UK solar could operate free of subsidy by 2020.

tank Thema1 and supported by a coalition of European companies.

The report, 'In Sight: Unsubsidised UK Solar', predicts that all three sectors of the UK solar market (ground-mount, commercial and domestic) will be able to compete without subsidy with traditional forms of energy within the next 10 years.

The think tank believes that the UK solar market will continue to benefit from falling solar hardware costs as well as a maturing supply chain which will see system costs converge with Germany.

"We are firmly convinced that solar will become the bedrock of the global power system going forward," explained report author Gerard Reid, a partner at corporate finance company Alexa Capital. However, the report makes clear that, in order for UK solar to realise its ambition of requiring no subsidy, policy support must be strong and consistent.

France launches 400MW PV tender

The French government in November launched a 400MW request for proposals for PV projects larger than 250kW.

The tender has 50MW ring-fenced for projects in parking facilities below 4.5MW in size. There is a 150MW allocation for rooftop projects and 200MW of ground-mounted projects. The ground-mount allocation is split with 75MW of capacity for projects below 5MW and 125MW for plants more than 5MW but less than 12MW.

Interested parties have until 1 June 2015 to submit their application.

In separate news in November, French energy minister, Ségolène Royal, awarded 40.7MWp worth of feed-in tariffs (FiTs) across 217 PV projects, in the third phase of a national tender process.

All the projects awarded the FiT were categorised as medium-sized, between 100kWp and 250kWp generation capacity. All the projects are expected to be completed and connected in 2016 and 2017.

Americas news

SEIA: US solar continues 'impressive growth'

The US enjoyed its second largest ever quarter for PV in the third quarter of 2014, installing 1,354MW, the US Solar Energy Industries' Association (SEIA).

SEIA said the installations represented an increase of around 20% on the previous quarter and a 41% increase on the same period of last year. In Q2 2014, the country installed around 1,133MW of PV, while last year, only 963MW was added in the third quarter.

In total, the US now has an installed PV generation capacity of 16.1GW – plus around 1.4GW of concentrator PV (CPV). The figures come from the US Solar Market Insight, which is published jointly each quarter by the trade advocacy group and GTM Research.

SEIA's president and chief executive Rhone Resch pointed out that effectively, a solar power project is completed and switched on every three minutes in the US.

Brazil's first PV power auction sets very low US$86.78/MWh mark

The 6th Reserve Energy Auction, conducted by the Brazilian National Electric Energy Agency (ANEEL) and operated by the Electricity Trading Chamber (CCEE) at the end of October was said to have generated intense bidding from a massive oversubscription.

After the longest auction Brazil has undertaken, 31 out of 400 PV project opportunities totalling 889.7MW were granted approval at providing electricity at the fixed price of US$86.78/MWh for 20 years, beginning on October 1, 2017.

CCEE had originally placed an aggressively low ceiling price for PV of US$105.69/MWh, but interest in the Energy Auction Reserve was significant with only one obvious outcome, a significant 17.9% discount to the ceiling price.

CCEE noted that the state of Bahia had the most projects, without providing further details. The remaining projects approved were spread over the states of São Paulo, Rio Grande do Norte, Ceará, Minas Gerais, Pernambuco, Piauí and Goiás.

Over 1,000 enterprises registered interest in participating in the auction with a total supply of 26,297MW of installed capacity being offered.

Middle East and Africa news

Uganda in line for first 20MW of large-scale PV

Uganda has fired the starting gun on its bid to become a large-scale solar player with the selection of four projects totalling 20MW.

The country's Electricity Authority has chosen two international consortia to develop two 5MW projects each following a competitive bidding process initiated at the start of 2014.

One is a Ugandan-Italian partnership between Simba Telecom and Building Energy, the other a collaboration between the Dubai-based renewables developer, Access, and Spain's TSK Electronica. The two consortia will build, own and operate two 5MW grid-connected projects each in Tororo and Soroti districts respectively.

The projects represent the first contracts to be awarded under the new solar element of Uganda's 'GET FiT' programme. This initiative to support private investment in renewable energy in the East African country is being run in conjunction with Germany's KfW development bank with funding from the EU Infrastructure Trust Fund.

Nigeria signs 1.2GW PV agreement

Global energy developer New Generation Power (NGP) has signed a memorandum of understanding with the Federal Government of Nigeria to deliver 1,200MW of utility-scale PV projects within the West African country.

Motir Seaspire, a specialist in construction and energy development, also signed the MoU for the estimated US$2 billion plan.

Although the Nigerian government has yet to identify the location of the projects, NGP said they were expected to break ground in 2015 and be operational within two years.

Once completed, the projects are expected to produce 590,400MWh of renewable electricity annually. Currently, 60% of Nigerians do not have access to power, despite the country's said enormous energy potential.

A number of plans for large-scale PV projects in Nigeria have been made in recent months, including 500MW in 2013 through a joint programme with Germany. However, none have yet come to fruition

Asia & Oceania news

India to boost national solar target to 100GW by 2022 - reports

India's energy minister, Piyush Goyal has said the nation's solar target is to be multiplied to 100GW by 2022.

According to a number of press reports in November, Goyal said the current JNNSM sola mission target of 20GW by 2022 would be pushed up to 100GW.

The government will work specifically towards grid parity, making solar bankable and the industry self-sufficient.

In August 2014, just after anti-dumping duties in India were ruled out, Goyal told solar developers, manufacturers and stakeholders that the government will provide full support for domestic solar manufacturing. "Renewable power is the future of the country and will be supported fully," a statement said.

Goyal has previously revealed the government is working on land access to set up utility-scale, and mega-scale solar power projects in the country.

SunEdison sets sights on Philippines with 300MW PV partnership

US PV energy provider SunEdison has finalised a partnership with Aboitiz Renewables that could see the pair build up to 300MW of PV in the Philippines.

Under the joint framework between SunEdison and Aboitiz, a subsidiary of local utility, Aboitiz Power Corporation, the pair said they would explore, develop, construct and operate up to 300MW of PV in the Philippines over the next three years.

The companies said they would begin the first in a "series" of utility-scale PV plants in the Philippines next year.

Solar has begun to make some headway in the Philippines lately, with the country's first utility-scale plant coming online in 2014. The island nation also has a project pipeline now exceeding 1GW, though there have been some question marks over the achievability of this because of various regulatory hurdles, not least the complexity of its feed-in tariff.

Source: Conergy

SunEdison has its eye on the projects in the Philippines.

News

Inverter market news

Shakeup in PV inverter company rankings continues

In the latest 'PV Inverter Market Tracker' report from market research firm, IHS, covering Q3 2014, the global PV inverter market continued to remain highly dynamic and regional players in booming markets making the most gains.

IHS said Chinese telecommunications company, Huawei, made the largest gain in global market share, with just over two percentage points of growth in the third quarter of 2014. Huawei's growth was primarily attributed to its market share expansion within the domestic Chinese market, which saw total inverter shipments increased steadily to 4.8GW, according to the IHS report.

Schneider Electric was the only European PV inverter supplier to gain any significant market share globally over the last year. This was said to be due to its increasing market position in the UK, France and other key European markets, as well as its growing presence in Japan and India.

SMA cuts guidance cut for second time

Shares in German inverter manufacturer SMA Solar fell 17.9% the day after the company announced it was slashing its 2014 sales and revenue forecasts and laying off more staff.

The company revealed in early December that it was revising down full-year sales guidance to €775 million to €790 million from the previous €850 million to €950 million, citing project delays in the UK and declining demand in key European markets.

It was the second time the company cut its guidance in 2014. In July, following poor first-half results, SMA downgraded its original forecast of €1 billion-1.3billion.

Solarmax parent company to file for insolvency

Sputnik Engineering, the parent company of Swiss inverter manufacturer Solarmax, has filed for insolvency in Switzerland.

The company said it had looked for alternatives but to no avail.

"The employees have been informed this morning and will stop working today until further notice," it said in a statement.

The company is not the first European manufacturer to struggle as the domestic market declined and competition increased.

"Solarmax had been the fifth largest supplier in the world in 2008, with a market share of over 4%," said Sam Wilkinson, research manager at market research firm, IHS. "Its market share has declined each year since, and it held a share of less than 1% in 2013.

Source: SMA Solar.

SMA Solar has cut its revenue forecasts for the second time in 2014.

Why p-type multi c-Si is seeing strong market-share gains

Finlay Colville, Solarbuzz, London, UK

ABSTRACT
Modules based on p-type multi c-Si technologies look set to dominate the PV industry over the next five years, continuing a trend that has developed over the past two years. This paper explores why high-efficiency p-type multi seems destined to remain the workhorse of the global PV industry.

Introduction

According to analysis in the new Solarbuzz "PV technology roadmap" report [1], modules based on p-type multi c-Si technologies are set to dominate the PV industry over the next five years. The findings from the new studies show that there has been a dramatic shift to high-efficiency (HE) p-type multi c-Si module production and shipments in the past two years, together with a softening in the focus assigned by many of the market leaders to mono-based technologies.

"There has been a dramatic shift to high-efficiency p-type multi c-Si module production and shipments in the past two years."

Across China and Southeast Asia, the push to improve multi performance – while driving down costs far more than in any other PV technology – has revitalized the prospects for multi c-Si technologies, and provides a stark contrast to the somewhat academ ic, and idealistic, PV technology roadmaps that have often been shown as a means of conveying technology leadership.

A subset of manufacturers is fixed on higher-quality c-Si shipments. At the top end, SunPower and Panasonic have no option but to use the highest-quality n-type ingots being produced. A few others have n-type capacity, but based on more standard cell architectures that do not need the silicon grade of a SunPower cell, such as those in Yingli's 'PANDA' modules.

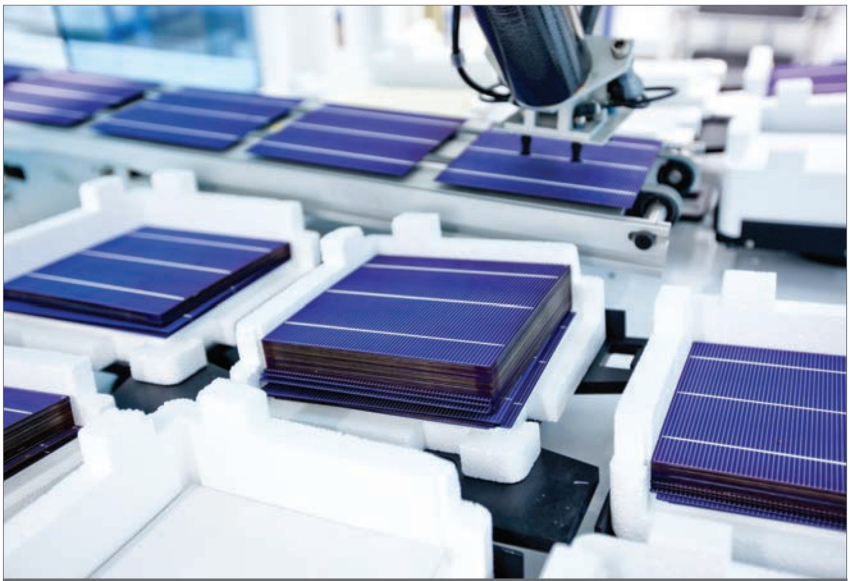
And then there are the cell makers that are able to flip lines over from mono to multi and vice versa, needing only p-type wafer supply. Taiwan cell makers have done the multi-to-mono flip of late, but it is questionable whether this is sustainable in the long term as the Japanese market finally succumbs to global price drivers over the next 18 months.

But p-type multi is winning the battle now, and is seeing strong market-share gains. In fact, it is really the HE multi wafer that has won the day here. Most – but not all – of the market-share gains from HE multi module shipments in the last 12 to 18 months can be tracked back to improvements in ingot growth. Interestingly, having an HE multi module is not necessarily contingent on having the best cell line. This has enabled selected Chinese makers (that have stuck to standard cell operation) to increase module power ratings in the past couple of years.

It is possibly time for some observers to change their views on p-type multi, with many having considered it of insufficient quality to feature prominently on PV technology roadmaps. There is no shortage of solar cell physics and chemistry on offer to back up this statement, but another crude way to look at this is as follows: if you keep improving multi quality, then at some point it becomes possible to do advanced process changes on multi that were previously only considered viable on mono. Indeed, adding the passivated emitter rear cell (PERC) structures will work quicker on mono (everything works quicker on mono), but that by no means precludes efficiency improvements on multi as the substrate quality keeps getting better.

It is no coincidence that the top two module suppliers to the PV industry (Yingli Green Energy and Trina Solar) are choosing p-type multi c-Si as their key offering to the industry from now on. Nor should it be a surprise that GCL is putting so much effort into having better ingot growth and wafer supply of p-type multi substrates to much of the key Asian suppliers today. Some may argue that the pull of Yingli, Trina and GCL alone effectively sets the deal in terms of HE p-type multi c-Si technology's domination, but there is more.

Perhaps one of the other factors in multi's resilience and potential can be found with REC Solar and Hanwha Q CELLS in their fabs in Southeast Asia. From a technology standpoint, REC Solar and Hanwha Q CELLS arguably have the most experienced c-Si R&D teams (outside of SunPower) in the industry, and are certainly aware of all the risks and opportunities that would come from adding any unknown process change (or anything that is prohibitively high cost) to multi c-Si manufacturing lines that are meeting customer needs.



Source: Hanwha Q CELLS.

Figure 1. Hanwha Q CELLS p-type multicrystalline PV cells.

Both REC and Q CELLS (Fig. 1) are staunch p-type multi c-Si cell proponents, with p-type multi module supply accounting for their entire end-market shipments. Expansions are p-type multi based, with module power increases again being mainly tracked back to the improvements in multi c-Si ingots in the past couple of years. Each company is tinkering with PERC additions, presumably once all front-side upgrades are complete.

As REC captured contract after contract for module supply recently in the USA, did anyone bat an eyelid at the fact that these entire shipments will be from p-type multi c-Si panels? Of course not: shipping 260–265W 60-cell panels (for rooftops or ground-mount) at the right cost point is readily accepted by the market. If need be, create a 72-cell equivalent (300W plus). But how many developers or engineering procurement and construction (EPC) companies are insisting that mono modules be supplied?

The new PV technology roadmap studies at Solarbuzz [1] involved looking separately at what technology means from every aspect of the solar PV industry, something that had been a key omission in all technology roadmaps outlined previously to the industry. In fact, in the past, roadmaps were typically compiled by scientists who were not necessarily privy to end-market activity, or by R&D teams at companies that often just took their lead from the scientists' wish-lists.

There is nothing wrong with that, but the previous roadmaps that claimed the big market-share swings to n-type – or (dare we say it) thin-film technologies – were just not of the real world. The reality was that the roadmaps were simply changed each year on the basis of what the end market was actually doing. And all too often, the end market was choosing simplicity and gradual cost reduction and small (but meaningful) efficiency gains. Every year, moreover, the momentum and critical mass of p-type multi manufacturing have only added weight and traction, raising the bar for almost every other competing PV technology.

> "Pulling apart every end market was one of the most valuable parts of the overall Solarbuzz PV technology roadmap methodology."

End-market pull on technology is made

Had the PV technology analysis been terminated once the study of end-market trends was complete, the conclusions would not have been that far off the final output from the whole-industry analysis on technology.

Pulling apart every end market – the rooftop supply activity, the commercial rooftop sector, and the small and large ground-mounted systems – was one of the most valuable parts of the overall Solarbuzz PV technology roadmap methodology. This was followed by looking at the project pipeline across all developers and EPC companies, and reviewing who supplies what and from whom. And at the micro-segment level (one specific country, one specific application segment), the trends were identified for c-Si versus thin-film, mono vs. multi, multi vs. HE multi, etc.

Just one of the final graphics to come out of this study is shown in Fig. 2. In this case, what is effectively the serviceable available market (SAM) for SunPower, Panasonic, TetraSun and Silevo has been extracted, to derive the forecast geographic end-market demand for c-Si premium modules. A secondary level of technology segmentation also falls out here, in that the split by country/region is provided for residential, commercial rooftops and ground-mounted segments. So almost by default, the roadmap starts to provide sales targets for technology-specific module suppliers, from both an application and a geographic standpoint.

Fig. 2 also shows that even the technologies with a small market share can have strong growth trajectories. Growing from 1 to 6GW sounds great, but remember that it is likely that 2014 will end up close to 50GW and that the growth trends to 2018 will remain strong. So even extracting 6GW in 2018 for premium n-type module supply (and similarly removing thin-film additions) still leaves a huge amount of market demand, and this is exactly where the p-type multi activity fits in.

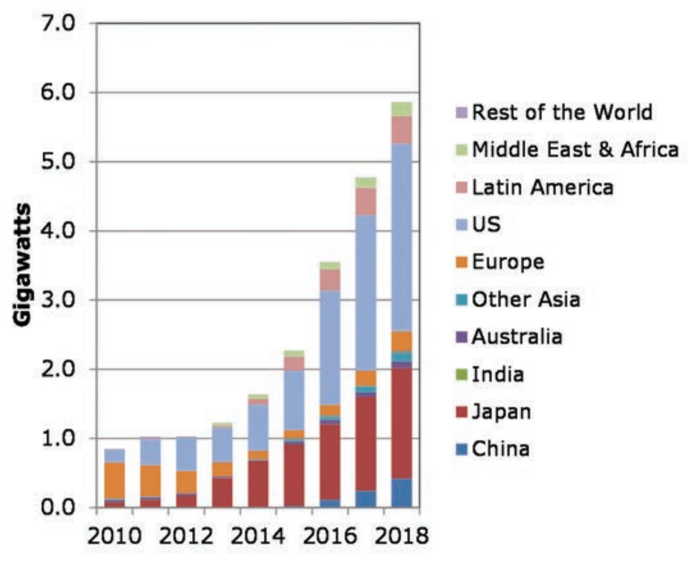
Analysis of mono and multi splits

Once the above two sub-segments are removed from the end-market technology analysis (premium n-type and thin-film), the focus then returns to the standard n-type, p-type mono and p-type multi debate. This therefore required a dive into all the activities of the tier-one supply-chain from polysilicon to ingot/wafer and cells and all the way down to the branded shipments of the top 20 module suppliers to the industry.

Eventually, it is possible to extract the p-type multi demand, and, as shown in Fig. 3, separate out in a way that shows the incredible gains made since 2011 by HE multi in the market. In effect, this derives empirically what was alluded to at the beginning of this paper: the market leaders continue to prioritize p-type multi, with the shift from standard to HE multi module supply being the catalyst in revitalizing what many had assumed was a technology destined to be replaced by the more esoteric alternatives.

The methodology used to derive the technology roadmap enables plenty of technology-related trends to be reviewed and discussed, down to process flow arrangements across cell makers, or technology shipments on rooftops, by country and technology type. One particularly interesting output, however, relates to the module power rating forecasts.

To do this, the focus was placed



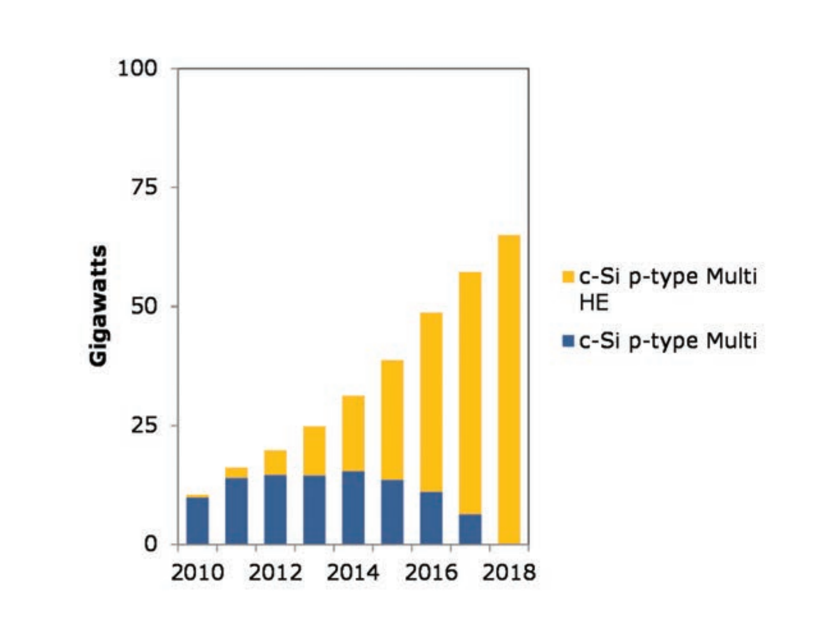
Source: Solarbuzz [1].

Figure 2. Global demand for premium c-Si premium modules: forecast shipment locations to 2018, derived bottom-up from end-market demand and project developer/EPC company/installer supply activity.

specifically on the module shipment volumes of the top 20 module suppliers, effectively removing variants that are offered to the market but whose market-share level is somewhat in the noise. Therefore, knowing what is being installed in the end market is essential here, not necessarily what is being offered on datasheets to the market.

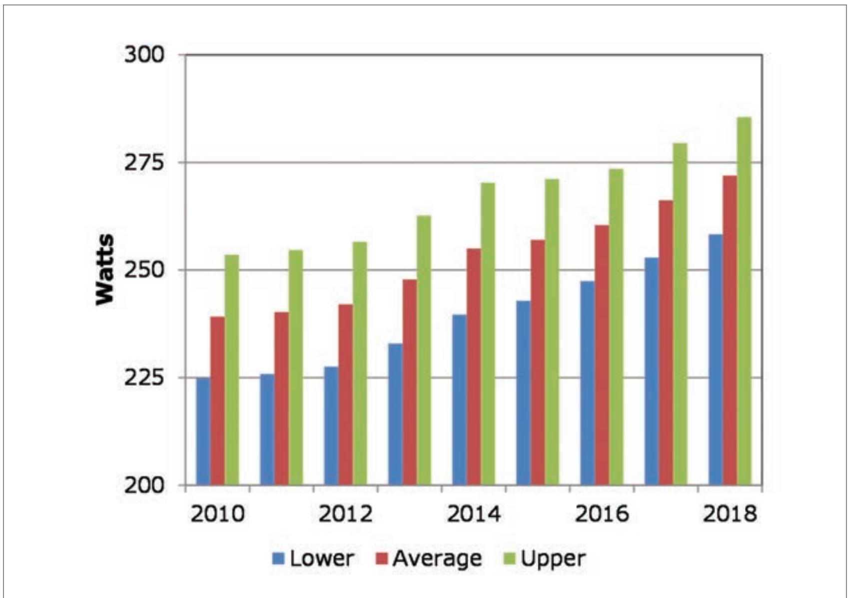
When 48, 60, 72, and 96 cell variants were considered, across 5 and 6" cell types, and splitting into the relevant premium n-type, mono and multi types, the end result was 16 c-Si module variants. The power ratings (historic, current and forecast to the end of 2018) were analysed for each of these 16 c-Si module types, and compared with existing data points from average mass production data of the top 20 module suppliers to the industry. But, if one module type has to be ring-fenced for display here, it is undoubtedly the 60-cell, 6" c-Si multi HE panel – the clear market-leader in the PV industry today.

Fig. 4 shows the trends in mass production for this module type, with typical upper/lower ratings that fall outside of the distribution curves. The strong growth in power ratings from 2010 to 2014 confirms the ingot/wafer trends discussed at the beginning of this paper. The slight upward trend again in 2017 and 2018 assumes that some of the cell changes (largely thought to be mono specific) are implemented in mass production for multi cells.



Source: Solarbuzz [1].

Figure 3. Most likely technology forecast for c-Si p-type multi variants: c-Si p-type multi is set to see further market-share gains until 2018, driven by the high-efficiency (HE) module variants that have helped salvage profitability across much of the upstream manufacturing segment during 2013 and 2014.



Source: Solarbuzz [1].

Figure 4. Historical, current and future panel ratings (Wdc-p, STC) for the industry's most popular module, the 6" c-Si p-type multi HE panel comprised of 60 cells.

> "For those looking to address a large segment of the PV industry, keeping a focus on p-type multi HE activity will be essential."

Conclusion and outlook

As materials and equipment suppliers review their strategies for the next few years, it is hard to imagine how anyone can choose to ignore the opportunity from the supply of p-type multi HE, unless the sole target is to play within more technology-specific lower-volume addressable markets. For some suppliers, this will be perfectly acceptable, with the strong growth in the end market ensuring ongoing supply. But for those looking to address a large segment of the PV industry, keeping a focus on p-type multi HE activity will be essential.

Finally, the evolution of technology supply and geographic variations will also have a direct impact on planned capacity additions. Are companies limiting themselves through choice of technology, in terms of which end markets to go after?

While a few gigawatts here and there is not going to change the overall picture in 2018, knowing what the competition is likely to be offering, and which countries and segments will be awash with p-type HE multi modules, is simply prudent housekeeping which should limit the surprises that might be encountered in the future.

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[1] Solarbuzz 2014, "PV technology road map report", September [http://www.solarbuzz.com/reports/pv-technology-report].

About the Author

Finlay Colville is vice president at Solarbuzz and leads the Solarbuzz team of analysts dedicated to PV market research and strategic consulting activities. He is also directly responsible for the "PV equipment quarterly" and the "UK deal tracker" reports. Dr. Colville holds a B.Sc. in physics from the University of Glasgow and a Ph.D. in nonlinear photonics from the University of St. Andrews.

Enquiries

Email: finlay.colville@solarbuzz.com

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Trina Solar to be crowned leading PV manufacturer in 2014, surpassing Yingli Green


Trina Solar has become the biggest module supplier of 2014.

Source: Trina Solar.

Based on analysis of the leading PV manufacturers and their latest shipment guidance for 2014, PV Tech has compiled the preliminary top 10 rankings for 2014.

Since the second quarter of 2014, a fight has been underway between Yingli Green and Trina Solar over which company would top the shipment figures after it also became clear that the likes of Sharp (ranked third in 2013) would not grow shipments.

PV Tech was first to highlight the battle between the two Chinese rivals in late August, just after Yingli Green had lowered its shipment guidance to be exactly the same as Trina Solar's at 3.6GW to 3.8GW.

However, Trina Solar has also slipped on its guidance, forecasting shipments to be in the range of 3.61GW and 3.66GW for 2014, after releasing third quarter results.

PV Tech also highlighted from shipment growth analysis that Yingli Green had become a laggard this year with shipment growth guidance given in the second quarter that would only generate shipment growth of 15% to 20%.

On the other hand, despite the lowering of shipment guidance by Trina Solar, it still expected shipment growth of between 40% and 42% this year, indicating that the number 2 ranked producer had the momentum over Yingli Green.

However, Yingli Green has released third quarter results and slashed its full-year shipment guidance to be in the range of 3.30GW to 3.35GW, resulting in shipment growth of only 3% to 4.6% compared to 2013.

On a shipment basis, quarter-on-quarter the battle between the two companies has been intense with Yingli Green quite a bit ahead of Trina Solar in the first quarter of 2014.

However, shipment figures swung the other way, despite Yingli Green posting shipments of 887.9MW in the second quarter. But Trina Solar had surpassed Yingli Green at 943.3MW.

With third quarter shipment figures just released, Trina Solar's shipment momentum has continued to rise, while Yingli Green's is slowing. Trina Solar shipped over 1GW in the third quarter and guided the same for the fourth quarter. Yingli Green shipped 903.4MW in the third quarter and guided similar levels for the final quarter of the year.

The shipment gap of approximately 300MW between Trina Solar and Yingli Green after both revised down shipments should be large enough for Trina Solar to secure the top-ranked PV manufacturer in 2014, with Yingli Green dropping to second position, after two years of reign.

Interestingly, in the last 10 years those that have reached the top-ranked position have failed to retain dominance for more than two years. This includes the likes of First Solar and Suntech Power Holdings.

Major ranking reshuffle in top 10

The PV industry continues to be highly dynamic and this is being reflected in some significant ranking reshuffles in 2014.

The PV-Tech Blog

By **Mark Osborne**

JinkoSolar has continued to build on its market share gains over the last few years and with shipment guidance of 2.9GW to 3.2GW, despite the wide range, is set to become the third largest PV manufacturer this year, moving up the rankings from 5th position in 2013.

With Canadian Solar tightening its 2014 shipment guidance to 2.72GW to 2.78GW recently and Sharp lowering its forecasts, JinkoSolar's momentum is impressive.

Only two companies are to retain the same ranking this year as last year – Canadian Solar, which is ranked fourth, and Renesola, ranked sixth.

However, the biggest mover is not JinkoSolar. Instead, JA Solar has moved up five positions from being ranked 10th in 2013 to being ranked fifth in 2014. The major leap by JA Solar reflects its switch from being a merchant solar producer to a major module supplier in only a few years. As PV Tech has already highlighted, JA Solar has the highest shipment growth guidance of 105% to 114% this year, while shipment guidance is 2.4GW to 2.5GW.

The other shipment growth laggards, including Hanwha SolarOne, Sharp and First Solar, all drop positions in 2014 compared to the previous year.

Hanwha SolarOne's 10-15% shipment growth is relatively anaemic, meaning it loses one position to be ranked ninth in 2014 with shipment guidance recently lowered to 1.43GW to 1.46GW.

First Solar also loses one position (ranked eighth) with shipment growth of 12% to 19% and guidance of 1.8GW to 1.9GW.

First Solar's lack of shipment growth compared to its peers in the top 10 rankings was made evident early in the year, when after a year of building large-scale utility projects its 2014 project pipeline was insufficient to keep production utilization rates at high levels, something that has persisted all year.

Sharp soared up the rankings table in 2013, due to the boom in Japanese PV installations on the back of a highly attractive FiT. However, primarily due to the introduction of a consumption tax in Japan, Sharp warned that it did not expect shipments in 2014 to meet 2013 levels. As a result, Sharp is guiding negative growth within the range of 5-9% for 2014 and therefore tops the laggards list this year.

The lack of shipment growth by Sharp has really impacted its ranking position given the fact that manufacturers with 2GW or more of nameplate capacity dominate the middle rankings and most importantly have shipment growth forecasts significantly higher. Sharp falls from third in 2013 to seventh in 2014.

However, there is a major battle happening over the 10th ranked company, with Wuxi Suntech rebounding this year and just hedging SunPower, Kyocera and Hanwha Q CELLS.

But only with final shipment figures from these companies will the 10th ranked company be known. The reason for this is how close shipment guidance ranges are for these four companies.

Wuxi Suntech has guided shipments of between 1.3GW and 1.5GW, SunPower 1.3GW to 1.4GW, Kyocera at 1.2GW to 1.4GW and Hanwha Q CELLS has guided 1GW to 1.2GW.

What is also interesting from the 2014 rankings compared to the 2013 rankings is that shipments of 1.3GW will be required to enter the top 10, up from 1.1GW required last year.

Also joining the battle outside the top 10 rankings has been Solar Frontier, REC Solar and SolarWorld. Indeed, REC Solar and SolarWorld are reporting strong shipment growth in 2014 and both adding moderate capacity in 2015. However, they would need to have more capacity and further shipment growth to properly challenge for a top 10 position.

Source: Yingli Green.

Flat growth for Yingli in 2014 saw it lose the top slot.

A year of recovery

Unquestionably, 2014 has been a recovery year for major PV manufacturers as supply and demand has rebalanced after several years of chronic oversupply. Effective capacity at the beginning of the year stood at around 45GW, which has had to expand to meet demand that looks likely to reach around 50GW in 2014.

Effective capacity expansions, primarily by tier-one module manufacturers and the majority of the 2013 ranked top 10 producers has been successfully moderated, indicating that lessons have been learned from the dire consequences of overcapacity and a two-year period of profitless prosperity.

Rank 2013	Rank 2014	Company	Guided shipments (GW)
C1	1	Trina Solar	3.61-3.66
2	2	Yingli Green	3.3-3.35
5	3	JinkoSolar	2.9-3.2
4	4	Canadian Solar	2.73-2.78
10	5	JA Solar	2.4-2.5
6	6	ReneSola	2.3-2.5
3	7	Sharp Corp	1.9-2
7	8	First Solar	1.8-1.9
8	9	Hanwha SolarOne	1.43-1.46
NA	10	Wuxi Suntech	1.3-1.5

Source: PV Tech analysis.

Company rankings for 2014 based on guided shipments.

Mark Osborne is Senior News Editor of Solar Media, publisher of Photovoltaics International