Twenty Third Edition

Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS

Fraunhofer CSP Multi-busbar technology: Increased module power and higher reliability at lower cost

ISC Konstanz Low-cost, high-efficiency solar cells for the future

PCCL Advanced methods for determining PV module process optimization potential

PICON Solar Cell metallization by screen printing: Cost, limits and alternatives

First Quarter, March 2014

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Cover image: Multi-busbar connector with vacuum chuck used to align the copper wires on a solar cell.

Image courtesy of SCHMID Group, SCHMID Technology Systems GmbH.

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Foreword

At the last time of writing this introductory column, the industry was abuzz with talk of a pending upturn. After two years of hard going for PV manufacturers, which had seen such giants as Suntech and LDK Solar go to the wall, all the signs indicated that the tough times were coming to an end. End-market demand was soaring and factories were running at their highest utilisation rates for several years.

Now it's official. The new year opened with a deluge of positive forecasts, with analysts predicting anywhere between 40-50GW of new PV demand in 2014 and even more next year. Deutsche Bank was sufficiently moved to predict a "second gold rush" for solar, in reference to the heady days pre-2011 when the PV industry went through its first phase of serious growth.

Sadly the broader supply chain won't see the full benefits of the upturn quite yet. The difficulties of the past two years mean manufacturers have had to hunker down and find ways to weather the storm, minimising any inclination on their part to adopt any radically new technologies. Although these same players are now seeing their order books begin to fill, this cautious mood is likely to prevail for much of the rest of this year as supply and demand find some kind of balance once again.

But if the levels of predicted demand materialize, it is inevitable that manufacturers will have to begin expanding capacity at some point. Indeed the first signs of this happening are beginning to emerge, with the likes of SunPower, Trina Solar and Canadian Solar among the big names already sketching out plans to expand later this year and next. The latest forecast from analyst firm NPD Solarbuzz is for capex to bounce back in earnest in 2015.

This will most likely be the point at which manufacturers start looking to introduce new technologies. It will also be the moment at which the effects of the upturn start to ripple out to tool manufacturers and equipment suppliers as manufacturers look for technologies that allow them to push down costs, improve efficiencies and yields, and remain competitive.

This issue of *Photovoltaics International*, our 23rd, offers key insights into some of the technologies that are ready to move from lab to fab in support of these goals.

ISC Konstanz offer a glimpse of what the low-cost, high-efficiency solar cells of the future might look like. On page 35 the institute's authors give an overview of what they call Konstanz' "technology zoo", encompassing their so-called BiSoN, PELICAN and ZEBRA cell concepts, all of which are aimed at increasing energy yield at the lowest possible cost.

Continuing in this theme, Fraunhofer CSP and Schmid explore how next-generation cell interconnection architecture can increase overall module performance. Their paper on page 79 discusses how advances in tabber-stringer and multi-busbar technology can be used to lower the overall size and cost per watt of modules while improving performance.

And with the drive on to find ways of reducing costs in areas other than the PV cell or module, we explore on page 100 the use of modular design in PV power plants. Focusing on leading power plant builders such as Belectric, SunPower and First Solar, Mark Osborne reveals how component and construction standardization in PV power plants is driving down the levelized cost of electricity generated from such installations.

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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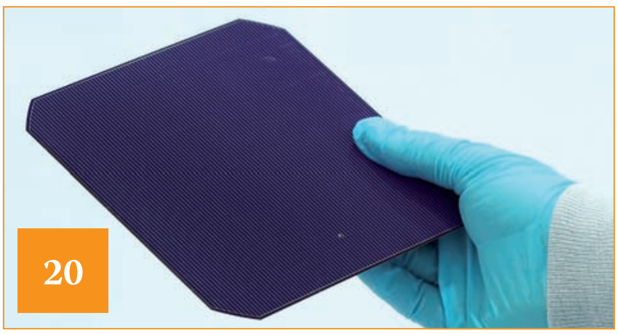
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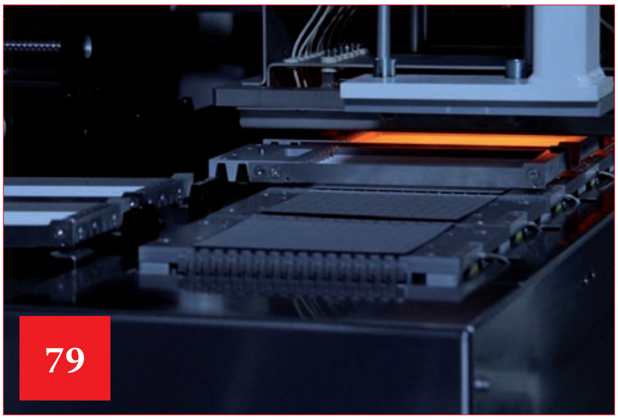


Fab & Facilities

News

SunPower plotting next-gen gigawatt-scale fab

Major PV energy provider, SunPower Corp, has revealed it is prepping plans for its next-generation 'Fab 5' manufacturing facility that would be on a larger scale than existing facilities.

The plant will be built as part of a major capacity expansion planned for 2015, once a new plant in the Philippines is complete.

Management had said in a conference call to discuss fourth quarter 2013 financial results that it had reeled in tool install dates for its new 350MW plant in the Philippines to the end of 2014, mainly due to a decision to install the first line that will use its existing technology platform.

The facility had originally been planned to house its next major cell (Gen 3) technology upgrades for its 'X Series' modules.

Source: SunPower.

SunPower's California Valley Solar Ranch project. The company is planning a gigawatt-scale fab to meet growing demand.

New manufacturing facilities

SunEdison's US$6.4 billion Saudi manufacturing complex moving forward

SunEdison's recently announced feasibility study to potentially establish a fully integrated PV manufacturing complex with FBR polysilicon production, in partnership with the Saudi Arabian government may be closer to reality than previously thought.

SunEdison recently revealed plans for the US$6.4 billion complex and highlighted that it was working with the Public Investment Fund (PIF) of the government of Saudi Arabia and the Saudi Arabian Investment Company (Sanabil Investments) on the feasibility of the project. The company noted that a preliminary study had already been carried out with the National Industrial Clusters Development Program (NICDP) in 2013.

However, comments from Ahmad Chatila, CEO of SunEdison in a conference call discussing fourth quarter financial results, strongly suggest that the possibilities of the potential massive deal contained a higher level of certainty than previously believed. They also tie in with SunEdison's plans to require as much as US$15 billion in annual project financing to support its plans to become a leading global downstream PV project developer.

ReneSola to open manufacturing facility in Japan

Chinese tier one manufacturer, Renesola, is to open a manufacturing base in Japan, in partnership with electronics trading company Vitec.

Vitec is headquartered in Tokyo with offices throughout Japan, the Asia-Pacific region and in California, supplying mostly semi-conductors and other electronic components.

Vitec announced news of the collaboration with ReneSola, with production expected to begin in April under the name Vitec Global Solar. Financial details and details of production capacity have not been revealed.

Source: OCI.

ReneSola's modules, here being used in Texas, are to be manufactured at a new plant in Japan.

Australian firm to fund 150MW cell and module factory in Sri Lanka

An Australian energy consultancy has signed a deal with the Sri Lankan government to develop a US$190 million PV cell and module factory.

The facility in the country's Board of Investment (BOI) trade zone, near the southern city of Hambantota, will have a capacity of 150MW. Sydney-based Energy Puzzle will provide the investment for the project, which was approved in January with the final agreement signed on 21 February.

Brazilian start-up to build 40MW PV module facility

Brazilian start-up Pure Energy Generation has received approval for its plan to build a 40MW PV module production plant in the Brazilian state of Alagoas.

According to the state department of communication, the facility will focus on module production and marketing.

At a regular meeting of the state council for economic and social development, Pure Energy Generation was granted approval for tax, credit and local incentive schemes to build the BR40 million (US$16.6 million) facility.

It will occupy 10.2 hectares of land and will have an initial production capacity of 40MW, with the option to upgrade capacity to 70MW. It will create over 50 jobs when it is opened. The new factory will be built at an industrial park, Polo

Source: JVG Thoma.

JVG Thoma has completed Nigeria's first module plant.

Multifabril Aprígio Jose Vilela, in Marechal, which hosts a number of chemical and plastics companies.

Nigeria's first module plant operational

Nigeria's first module manufacturing plant has been completed and is now operational. The plant, in Sokoto, has been built by German firm JVG Thoma and will produce the company's 'Desert' range of modules, which have been designed to operate in extreme conditions.

First announced last summer, the plant was part financed by the World Bank and will have a 10MW nameplate capacity. A PV array built next to the plant will supply it with regular power.

Capacity Expansion

Canadian Solar planning module capacity expansion to 3GW

PV energy provider, Canadian Solar, is considering increasing production capacity to 3GW in 2014. In SEC filings related to its latest stock offering to raise around US$200 million, the company noted that one of the key reasons for raising capital was for further expansion of manufacturing capacity to 3GW to meet growing demand.

Canadian Solar has become increasingly focused on the downstream PV power plant project development sector and currently said it had a 'late-stage' project pipeline of around 1.3GW with projects located in the US, Canada, Japan and China. The company also noted that it's early to 'mid-stage' project pipeline stood at 3.2GW.

OCI restarting 10,000 MT polysilicon capacity expansion plan

Korea's largest polysilicon producer, OCI said that it would revive plans to add polysilicon capacity to meet expected future demand. The company had previously suspended plans to carry-out a major de-bottlenecking operation at its P3 facilities due to weak demand and falling prices.

However, benefiting from low import duties to China in comparison to some of its major rivals based in the US, OCI said that its P3.9 debottlenecking plan to increase annual capacity by 10,000 MT, while reducing the overall manufacturing costs by US$2/kg, would commence in the first quarter of 2014.

The P3.9 debottlenecking would cost around US$110 million with commercial production planned for the third quarter of 2015. After the capacity expansion at P3 polysilicon plant, total capacity would stand at 52,000MT. However, OCI's 'Gen 3' expansion plans, which would increase polysilicon production by 44,000MT and organised in two phases, would remain suspended, according to the company.

Pufin Power to ramp 'made in Europe' cell and module production

The PV cell and module manufacturing operations of Dutch firm Pufin Power are to increase their production capacity after securing a supply deal with French distributor Thomson Energy.

Pufin said the deal would allow the company to increase capacity of its three manufacturing subsidiaries, Solland Solar Cells, Elifrance and El.Ital, by around 50%. Solland Solar Cells is expected to ramp its production of polycrystalline cells from 100 to 150MW a year.

Meanwhile, Pufin's module manufacturing arms El.Ital and Elifrance are expected to increase their capacity to 70MW and 40MW respectively; currently their combined capacity is 70MW annually. Pufin Power did not disclose further details of the deal with Thomson, but said it allowed the company to press ahead with planned increases to its production capacity.

Downsizing

REC Silicon not able to expand polysilicon production in 2014

Major polysilicon producer, REC Silicon, has said polysilicon production in 2014 would be lower than 2013 levels due to outages at its Silane II and IV facilities.

The former business unit of Renewable Energy Corporation (REC) reported polysilicon production in 2013 of 19,764MT, down from a peak in 2012 of 21,405MT.

REC Silicon said that it was targeting production of 19,400MT, a slight decrease compared to 2013, due to the outages and shutdown of its Silane I facility and increasing silane gas sales, due to production halts after an explosion and fire at Mitsubishi Materials polysilicon plant in Japan.

REC Silicon also noted that there were no plans in 2014 to reopen its shuttered Siemens-process polysilicon plant at its Moses Lake facility. The company said that polysilicon production in the first quarter of 2014 would be around 4,340MT.

SunEdison undertakes further polysilicon production consolidation

SunEdison has said the polysilicon ingot production operations for its semiconductor customers would be consolidated with the full closure of its facilities in Merano, Italy, and the transfer of 200mm diameter ingot production from St. Peters, Missouri to other overseas facilities.

Source: SunEdison.

SunEdison has announced the full closure of its polysilicon ingot plant in Merano, Italy.

Source: Trina Solar.

Trina Solar has acquired a stake in Hubei H Hongyuan PV Science and Technology.

The polysilicon facility in Merano was initially shuttered in December of 2011, due to declining market demand from key European semiconductor customers for 200mm wafers.

However, SunEdison said the associated electronic grade TCS (trichlorosilane) operation at the plant would also close indefinitely.

A total of approximately 200 employees at the Merano polysilicon plant and approximately 35 employees at the TCS plant were expected to lose their jobs as a result of the closures, as soon as the plant shut down.

Acquisitions

Trina Solar adding 420MW in solar cell capacity with JV

Tier one PV manufacturer, Trina Solar, is acquiring a majority shareholding in Hubei Hongyuan PV Science and Technology, a solar cell producer in China.

Trina Solar said it would form a joint venture with Shenzhen S.C. New Energy Technology Corporation, the owner of Hubei Hongyuan PV Science and Technology, taking a 51% stake in the solar cell producer with the operations renamed as Hubei Trina Solar Co., Ltd.

The partners said that the existing production facilities would be expanded to a capacity of 420 MW by mid-2014.

Consortium led by Taiwanese and Japanese firms to acquire aleo solar

Robert Bosch subsidiary, PV module manufacturer aleo solar is to be acquired by Taiwan-based solar cell producer, Sunrise Global Solar Energy and Japanese manufacturing machinery producer, CHOSHU Industry.

Aleo solar said in a statement that “significant parts” of the company, primarily its module manufacturing and module sales operations, would be sold to the consortium’s European JV company, SCP Solar GmbH.

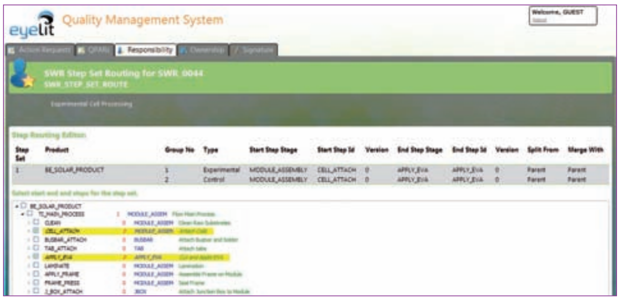
Bosch was said to have agreed to financially support aleo solar through the acquisition proceedings and provide additional funds in the course of liquidation of the company without having to file for insolvency.

Aleo solar said it would receive a token €1.00 for the purchase but SCP Solar would receive €10 million from the company as part of the acquisition.

Bosch has agreed a payment of €31 million to aleo solar in a compensation package.

Product Reviews

Eyelit



Eyelit launches Version 5.1 of MES with capability to manage R&D products

Product Outline: Eyelit has started the general availability of version 5.1 of its ‘Eyelit Manufacturing’ suite of MES (Manufacturing Execution System) software with key enhancements that enable engineers to quickly configure special instructions and processing that enforce special work requests (SWRs) for research and development projects.

Problem: When new products such as solar cells and modules are developed, they are typically produced on dedicated R&D lines, which can vary from real-world manufacturing lines and therefore create different results. Providing engineers with the ability to produce R&D-based products on actual manufacturing lines could reduce variance and speed product to market cycles.

Solution: The Eyelit 5.1 release was developed in close collaboration with customers to provide more informed decisions for manufacturing efficiency and quality, and further accelerate new product introductions.
The new ‘Eyelit Special Processing’ module helps manufacturers to design experiments and test evolving processes and products. This enables engineers to quickly configure special instructions and processing that enforce special work requests (SWRs) for research and development projects.
The new ‘Eyelit Advanced Dispatching’ module helps manufacturers to systematically determine relative processing priorities and tradeoffs, which will improve sequencing of work.

Applications: Manufacturing Execution System including R&D products.

Platform: The Eyelit Platform has a graphical ‘Scenario Builder’ for end-users to configure flexible conditional manufacturing, as well as business-process and quality-management workflows. In addition, new highlights of the ‘Eyelit SPC’ module include enhanced charting, filtering, calculations, metrics, and Nelson control rules.

Availability: Currently available.

Edwards

Edwards’ new large capacity STP-iXA4506 turbomolecular pump offer higher speeds and throughput

Product Outline: Edwards has launched the STP-iXA4506 large-capacity turbomolecular pump (TMP), designed to deliver significant savings for cost-sensitive manufacturers of semiconductors, flat panel displays, LEDs and solar modules using PVD tools.

Problem: Increasing pumping speed and overall gas throughput in PVD applications provides the opportunity to reduce the number of TMPs required, in turn reducing unit and maintenance costs.

Solution: The new STP-iXA4506 turbo pump is the all-in-one solution with improved pumping performance. It pairs Edwards’ latest rotor design with the well-established, highly reliable, on-board controller of the iXA series, to maximise the allowable gas throughput and minimise the number of pumps required for high-flow processes, particularly in solar and flat panel applications.
The fully integrated controller eliminates the need and cost of cables and a separate controller rack, resulting in a compact package that is fast and easy to install in a variety of applications. Magnetically levitated turbo pumps are used instead of mechanical bearings, which practically eliminates the cost of periodic maintenance.

Applications: The STP-iXA4506 can be used for a wide range of large-volume, high-flow applications, including semiconductor etch, LCD etch, glass coating, solar PVD and coating PVD.

Platform: The pump’s high speed (4300 l/s N2) and throughput (up to 4300 sccm N2), combined with its ability to efficiently pump both light and heavy gases, make the STP-iXA4506 ideal for a wide range of large-volume, high-flow applications. Its tightly integrated design includes a completely sealed electronic module for robust, reliable operation in the most demanding factory environments. When needed, a thermal management system can be added to reduce the accumulation of deposits and particulates from process byproducts.

Availability: February 2014 onwards.

Local PV manufacturing

Matthias Grossmann, Viridis.iQ GmbH, Konstanz, Germany

ABSTRACT

The investment case for the establishment of PV manufacturing hubs in emerging regions became bleak as c-Si PV manufacturing capacities in China ballooned from 2004 to 2011/12. The resulting supply overhang, with dramatic price decreases throughout the PV value chain, led to severe margin compressions and ultimately to closures, insolvencies and postponement of expansion plans by incumbents across the board. A common misperception by private and public decision makers alike – reflected in the recent escalation in global trade disputes – is that products made outside China are, per se, not competitive. In contrast to this mind-set, and on the basis of experience in numerous development projects, the author argues that new entrants have multiple instruments available that can make local PV manufacturing plants commercially viable in many regions of the world.

China, a global powerhouse in PV

After having witnessed – possibly not without envy – the staggering development of the semiconductor and electronic component industries in neighbouring countries such as Korea and Taiwan, the government of China seized the chance and did not miss out on the PV market opportunity.

It took China only eight years to increase its share of global manufacturing capacity from a meagre 7% by the end of 2004 to over 50% in 2012. This tremendous expansion of the relative share held by China-based production capacities took place in a PV environment with extraordinary global growth rates on both the supply and demand sides. Only recently, with the start of the PV market shake-out at the beginning of 2011, did capacity additions level out (Fig. 1).

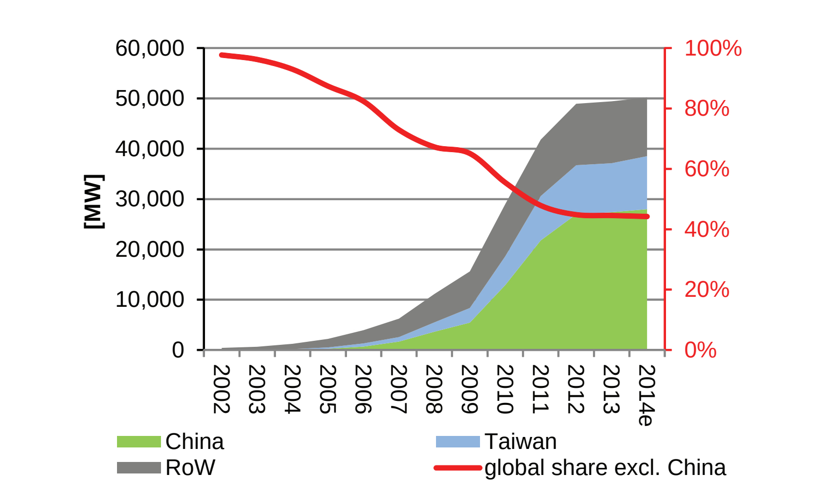
The major driving force on the supply side of the equation has clearly been mainland China, as a simple comparison of compounded annual growth rates (CAGRs) on capacity additions for selected regions reveals (Fig. 2).

The consequential build-up of excess capacity led to an unprecedented and prolonged price decrease on virtually all levels of the PV supply chain. This brought prices close to or even below leading manufacturers' short-term marginal costs, a price point that can only be defended over a short duration in a market-based economy.

> "PV subsidies are seen as tools that could be deployed in an instrument mix that is designed to foster the development of a local production cluster."

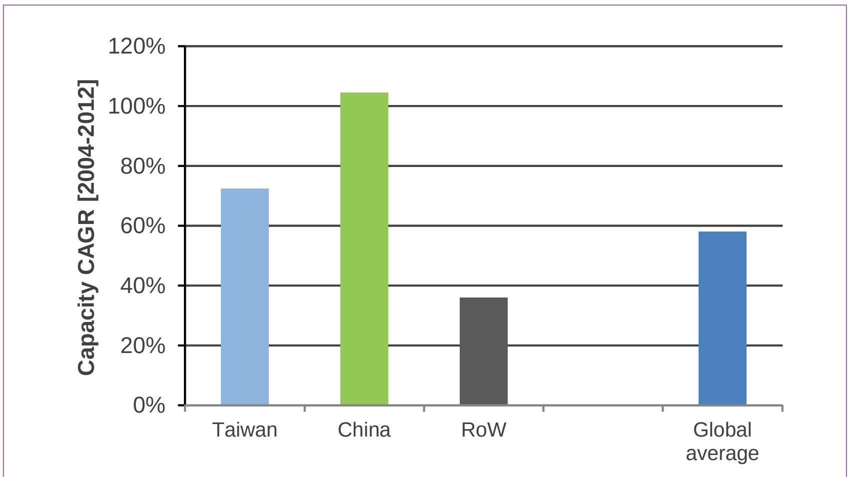
The resulting market clearance, with the failure of some renowned higher cost producers in the Western hemisphere, led to allegations that China-based manufacturers engaged in price dumping. The trade-related aspects of PV subsidies are discussed in the final section of this paper, as these are seen as tools that could be deployed in an instrument mix that is designed to foster the development of a local production cluster. However, the dispute is also seen as a source of distraction, as it deters decision makers from following a compact but comprehensive regional strategy that takes a holistic approach to promoting local installation as well as production.

PV power producers benefitted to a great extent from the unforeseen



Source: Viridis.iQ GmbH estimates

Figure 1. Global c-Si production capacity.



Source: Viridis.iQ GmbH estimates

Figure 2. Capacity CAGR 2004–2012 by region.

module price erosion of the order of 70% over the period 2010 to 2013 (Fig. 3). The improvement in the economics of PV systems resulted in a dynamic end-market environment with flourishing and broad-based demand from numerous countries around the world. The price elasticity of demand contributed to a long-anticipated transition process from subsidized markets to unsubsidized ones. The demand from new PV markets basically overcompensated the negative volume impacts caused by the curtailment of support schemes in many European countries.

These macrodynamics with flourishing installation volumes, failing business models and escalating trade disputes led to a subdued interest in local manufacturing in regions that are at the same time embracing the value proposition of PV power plants. In that respect the following aspects will be scrutinized in more detail:

- Local business models for integrated c-Si PV production, including depth of vertical integration, location-specific factors, collaborations, etc.

- Empirical evidence on the effectiveness of infant-industry protection in the PV industry (lasting until such measures are subject to formal challenge).

Local PV business models

The essential and most important aspects that need to be analysed at the outset of any business development initiative are addressable market size, competitive environment, supply chain options, and finance and investment needs, as well as country-specific conditions that might influence any of the aforementioned areas. Of course, an early-stage feasibility assessment covers many more vitally critical facets, such as the optimal technology choice, scale, material and mass flows, specification of infrastructure requirements, site selection, environmental assessment and initial project realization planning. However, an early-phase review of the first-mentioned key commercial-, financial- and market-related aspects is of advantage in that it might save precious time in the case of it leading to a clear indication that the project is not viable.

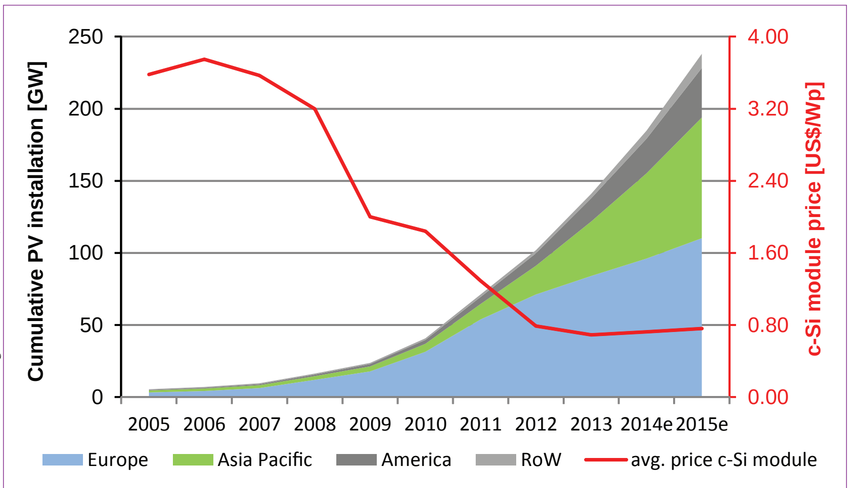
The listing of elements from diverse areas such as commerce, technology and engineering underpins the complexity of an industrial due-diligence process (Fig. 4). Further, the elements not only within the individual field but also from different areas influence each other, which leads to a multiloop and iterative planning process that relies on interdisciplinary expertise.

The decision process increases in complexity when the level of vertical integration is taken into consideration. For example, the crystalline silicon value chain virtually relies on three different industries and consists of five major process steps.

The sheer number of elements that needs to be considered in a holistic planning process to reach a sensible continuation or discontinuation decision exemplifies the magnitude of levers that can be utilized in order to improve the global competitive position of a new plant. Here, the most important areas that should be focused on during early pre-realization planning phases are:

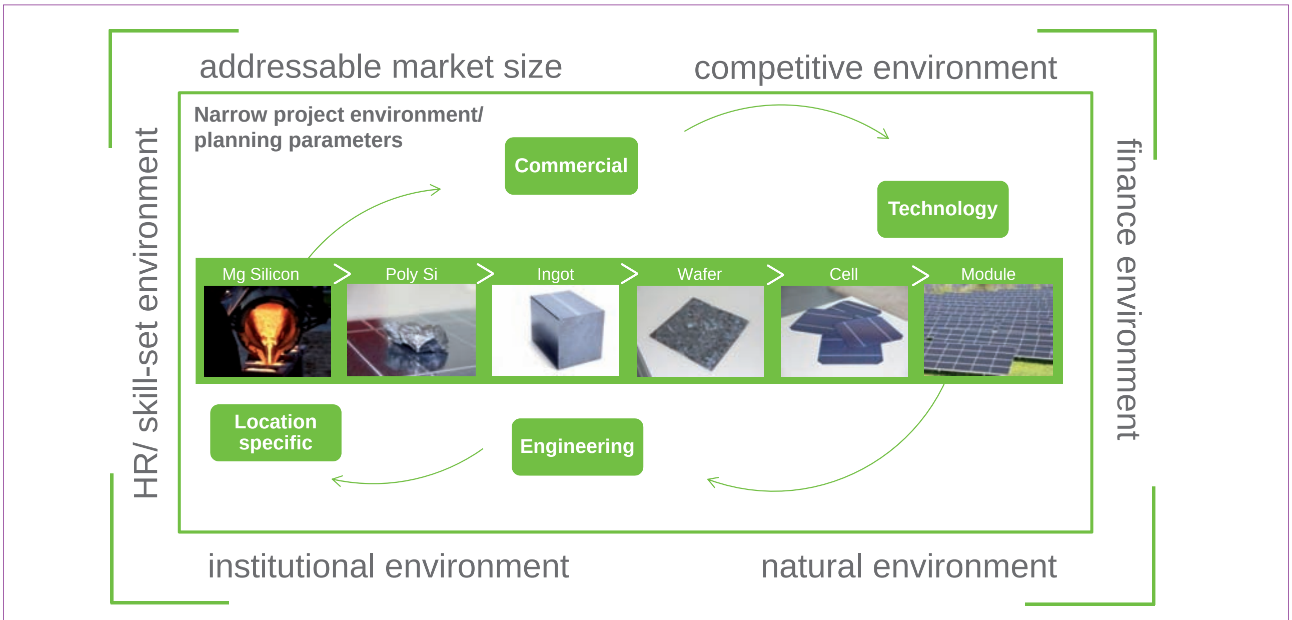
- Determination of the local and regional market size and supply structure in the near to mid term (subsidized and unsubsidized).

- Estimation of production costs in order to determine adequate capital-return-



Source: EPIA, PVinsights.com, Viridis.iQ GmbH estimates

Figure 3. Cumulative installations vs. price.



Source: Viridis.iQ GmbH

Figure 4. Complexity of project environment.

based average selling price (ASP) estimates, e.g. sustainable pricing.

- Supportiveness of the institutional environment for PV system adoption, e.g. renewable purchase obligations (RPOs), net-metering, feed-in tariffs (FiTs), licensing, etc.
- Country-specific advantages along the value chain, e.g. procurement- or product-related.
- Availability and extent of subsidy packages for fixed infrastructure investments.
- Political willingness to implement infant-industry protection mechanisms.

The transformation taking place in the PV installation market is largely driven by an increased interest from regions or countries that are situated in the 'sunbelt', with stable and high irradiation levels and low variation in seasonal daylight time. There are some commonalities in the motivation for moving forward into PV:

- Independent power producers (IPP) striving to reduce electricity bills as the commercial tipping point is reached for residential-, commercial- and in some instances even utility-scale applications in many regions.
- Generation close to the point of consumption in order to reduce investment in grid infrastructure, with decentralization and rural electrification playing a part in this.
- Diversification of the electricity generation profile in order to increase energy security and decrease dependence on fossil fuels.
- Meeting of mandated renewable targets that were formulated to lessen the negative impact of CO_2 emissions.

These factors have contributed to an unforeseen impetus in project development activities in various countries around the world. These emerging PV markets sometimes reach project pipelines in the multi-GW range, which translates into infrastructure investments of a couple of billion US$. Understandably, this has led or contributed to (cautious) uptake in interest in local production opportunities in some countries, as political decision makers are determined to capitalize on local installations and increase domestic value creation.

An assessment of the addressable market size that could eventually be served by a local PV production cluster is of significant importance for two reasons. First, target capacities and depth of vertical integration as well as phasing options must be defined. Second, a sufficient market size is a necessary pre-condition in considering the implementation of local content requirements (LCRs), which – by all standards of definition – conflict with World Trade Organization (WTO) agreements.

The imposition of LCRs in markets of inferior size is considered to be economically unfeasible, as the trade-barrier-related harm will most likely not be counteracted by social welfare gains. These benefits can potentially be harvested through protective measures that are intended to safeguard the uptake of an infant industry in an otherwise intense global competitive environment.

Apart from potential institutional provisions that might shield against competitive pressure in prospective off-take markets, other location-specific factors that influence the absolute level and slope of the supply curve play a crucial role in industrial PV development projects as well [1]. For example, Viridis.iQ GmbH receives many enquiries from regions that are blessed with vast reserves of hydrocarbons.

The motivation to investigate the 'PV option' builds on the expectation that a sustainable advantage from cheap energy could be reaped in the energy-intensive upstream segment of the c-Si value chain, namely the production of metallurgical silicon (mg-Si) and the subsequent purification to polysilicon (poly-Si). In addition, it is finally being acknowledged that rapidly depleting resources are precious and should not be wasted in subsidized local energy markets. In this regard it constitutes an attempt to internalize negative externalities in an inhomogeneous and discriminatory manner, e.g. a general increase in electricity rates, with preferential treatment of selected industries.

Other regions that show interest in the establishment of a local PV production cluster might not have anything else to offer other than a thriving installation market. These regions typically strive to decrease the

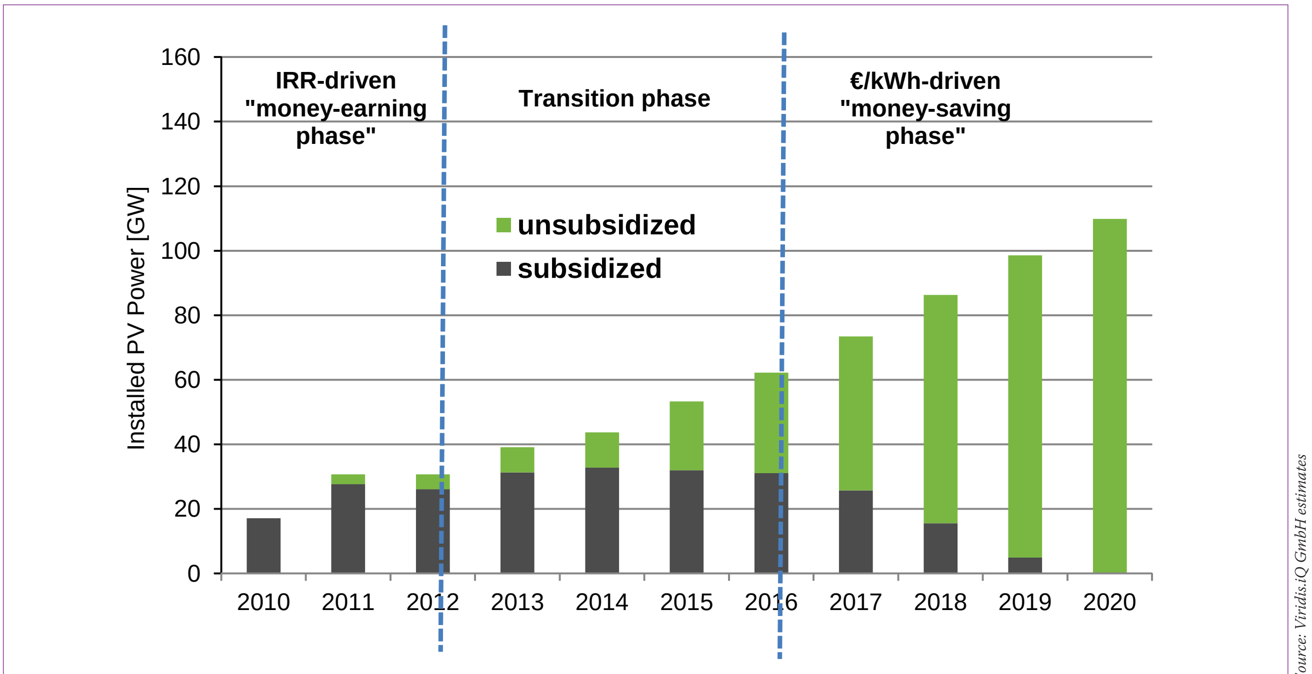


Figure 5. Global PV market in transition.

dependency on fossil fuel imports and provide cheap PV peak-power shaving capacity during the daytime.

"Production scale and good accessibility to the global PV supply network can partially compensate for higher new-entrant production costs."

In these cases Viridis.iQ GmbH discovered that production scale and good accessibility to the global PV supply network can partially compensate for higher new-entrant production costs. This is especially true when intermediate products, e.g. wafers and/or cells, in the c-Si PV value chain are offered at or below marginal costs.

It is at this juncture that the optimal depth of integration is defined and a reasonable project realization, as well as a phasing strategy, is compiled. As stated, in the optimal case the execution plan should be flanked by various political measures that increase the visibility to potential investors and mitigate scaling disadvantages which exist in comparison with major Asian production hubs that churn out products on a vastly depreciated asset basis.

This raises the question of how a new entrant can compensate for the disadvantage of carrying a higher amount of fixed assets relative to production volume. As already mentioned, a major advantage of almost all established players is that many are operating on a widely depreciated capital stock, with a corresponding positive effect on total production costs. This statement holds for the complete value chain in the c-Si segment, beginning at poly-Si purification. For this reason a diligent investigation of project-specific advantages – such as location factors, scale and supply chain as well as technology differentiation potential – needs to be considered in a holistic cost-estimation and benchmarking process.

Even though each project is unique with regard to operator model, scale, deployed technology, procurement conditions, and labour and energy costs, it is still worthwhile to investigate typical ranges for main cost categories. This exercise reveals the key areas of concern for the different industries involved in the production of c-Si PV modules.

The following high-level cost breakdowns are based on ranges derived from different real-world assessments. The relative ranges are modified in this respect, as they have been based on a standardized electricity procurement rate of US$0.06/kWh, a value that can legitimately be regarded as undercutting a global average of a peer group from major upstream and downstream production hubs (Fig. 6).

The high-level cost types that have been considered in the breakdown for the three industries under investigation are:

- Electricity
- Depreciation
- Materials
- Labour (production)
- Other (e.g. maintenance, SG&A)

The metallurgical silicon production process, defined as a refinement of minerals, relies primarily on the availability of natural resources, basic chemicals, energy in the form of electricity, and capital-intensive equipment. In a fully utilized plant with a minimum production capacity of 33,000MT per annum, the three main cost types – raw materials, depreciation and electricity – make up ~80–90% of total unit costs (Fig. 7).

The key cost drivers in the category 'raw materials' exhibit a range of approximately 15% around the median value: this is attributable to variations in specification and in cost, insurance and freight (CIF) markups. The electricity rate has been fixed and its variation in relative unit costs is a function of changes in the other parameters. The depreciation charges are dependent on site-specific parameters (e.g. ground levelling, foundation, etc.), equipment selection and operator model; these factors can be influenced positively by subsidy packages. A process of global benchmarking to relative capital investment figures reveals that incumbents are further up the learning curve and save on investments in comparison to new entrants. In addition, the contribution of the labour force to unit costs is minor. These

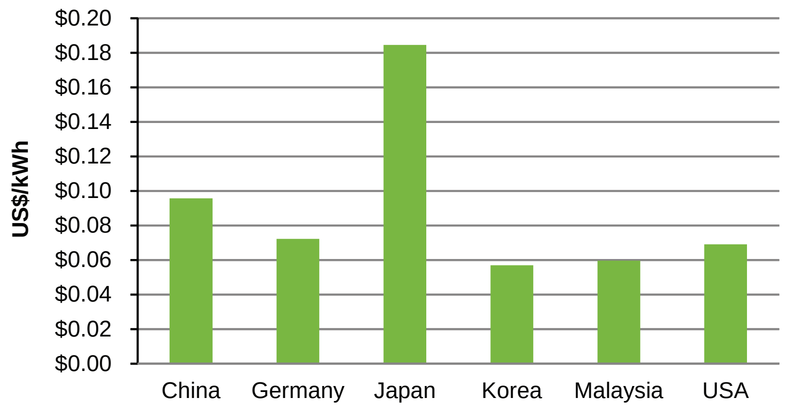


Figure 6. Average industrial electricity rates.

Source: Compiled by Viridis.iQ GmbH from various sources

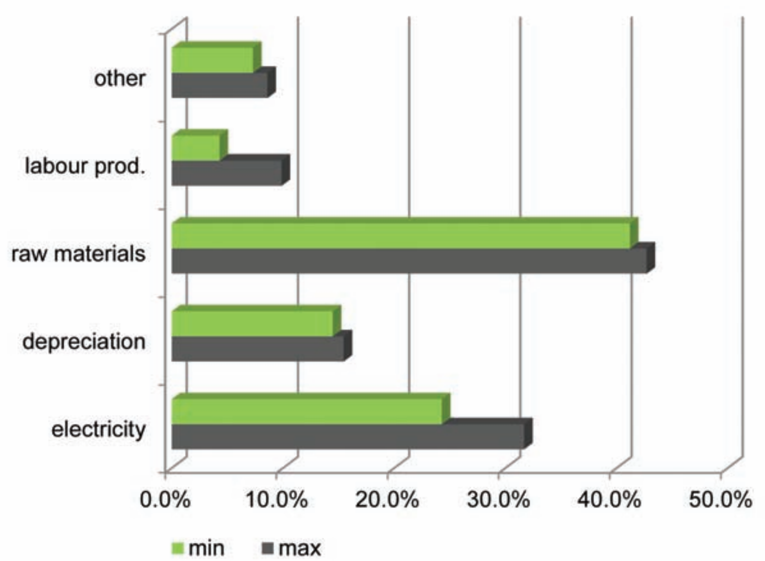


Figure 7. Mg-Si ranges by cost type (relative).

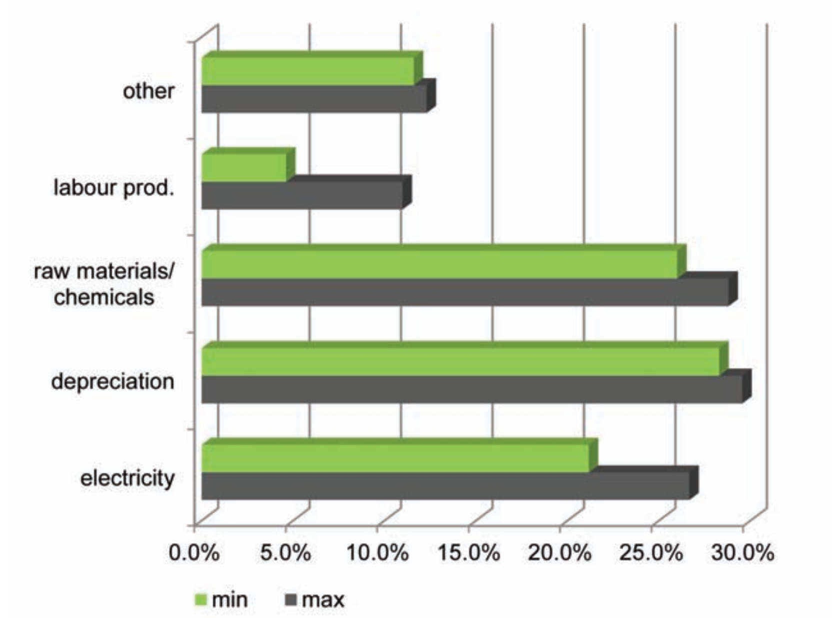
Source: Viridis.iQ GmbH

have been varied by a factor of three to reflect labour cost discrepancies between developed and emerging economies. This range of variation is fixed and is also applied to subsequent sections of the value chain, namely poly-Si and c-Si PV downstream.

Depreciation costs lie in the mid-teen percentage range and are therefore the third largest cost driver: this constitutes a potential competitive disadvantage for any new entrant, since established players are operating on a decreased asset basis. This relative disadvantage is a major concern in the subsequent production steps, as many established poly-Si and integrated c-Si PV module manufacturers have registered significant depreciation charges over the course of the past two years.

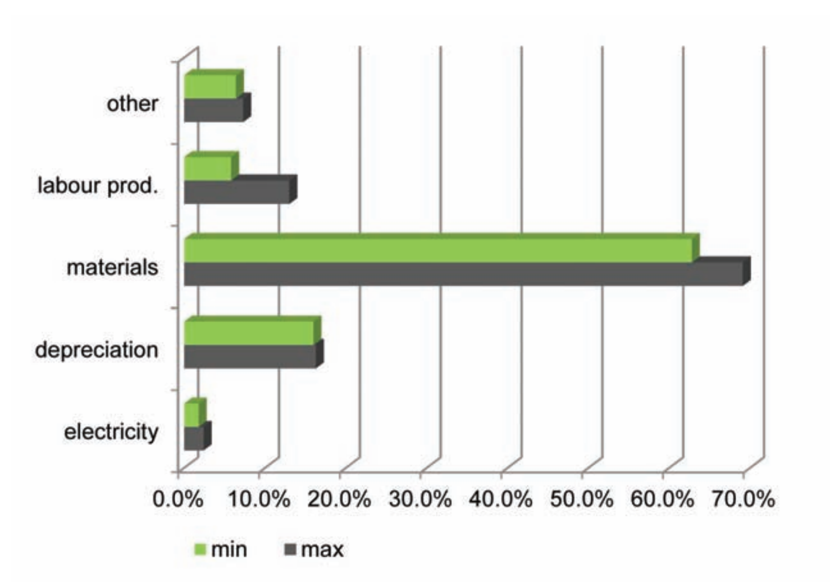
The Siemens-based chemical refinement to poly-Si is the most capital-intensive step in the integrated c-Si PV value chain. Metallurgical silicon is used as feedstock, and various chemicals and thermal treatments are employed in the subsequent decomposition, distillation and deposition steps: all these substances are collectively allocated to the category 'raw materials / chemicals'. The minimum and maximum parameter settings relate to projects with a capacity of more than 5000MT per annum.

The three biggest cost types constitute roughly 75–85% of total unit costs (Fig. 8). The dispersion in the relative contributions of the individual cost types is less pronounced than in the mg-Si case, which means that 'raw materials / chemicals', 'depreciation' and 'electricity' have almost the same impact on poly-Si unit costs. The category 'raw materials / chemicals' is influenced to a great extent by the availability of process chemicals in close proximity to the designated production site. Again – depending on the specific material, chemical or medium – the reference procurement prices exhibit a maximum spread of 40%. The depreciation charges are based on capital investments that are benchmarked, at the low end, to experienced Tier 1 producers and, at the high end, to new entrants. In terms of actual numbers, the investment ratios vary in the range US$87–114/kg, which equates to a relative spread of approximately 13%. The electricity unit procurement cost has been fixed at US$0.06/kWh.



Source: Viridis.iQ GmbH

Figure 8. Poly-Si ranges by cost type (relative).



Source: Viridis.iQ GmbH

Figure 9. Downstream PV ranges by cost type (relative).

This brings the discussion back to the aforementioned longevity aspect, in the sense that actual economic life of the equipment usually exceeds the useful life assumption made at the outset of the investment. The exact amount of poly-Si produced using depreciated equipment has most likely increased over the past two years, as many manufacturers registered considerable depreciation on their capital stock in the light of the weak pricing environment. This in turn has exacerbated the spread in total unit costs for material produced using operational equipment compared with expected costs at a greenfield site operated by an incumbent or new entrant.

These temporary competitive advantages enjoyed by existing manufacturers constitute a market-entry barrier which might discourage public decision makers from industrial development initiatives in regions that otherwise possess location-specific qualities which are superior to the actual site characteristics of existing plants. Regional benefits are usually realized in areas such as procurement, trade and institutional environment, as well as proximity to promising off-take markets.

In recent assessments for different locations, location-specific benefits, in combination with a price reversion assumption to a level at which Tier 1 producers would earn a risk-adjusted return on incremental capacity expansions that is above zero, showed an economically feasible investment case for local poly-Si production.

Moving now to the downstream segment of the integrated c-Si PV value chain – namely the ingot, wafering, cell processing and module assembly stages – the influence of materials on total unit costs becomes even more striking (Fig. 9). Further, the electricity consumption cost contribution can almost be neglected, while labour intensity, depending on the underlying remuneration schedule, can extend into the high teen percentage range. The two largest cost drivers in the material part of the downstream segment are feedstock and module components. The latter category – materials for module assembly – is a convenient starting point for supply chain investigations.

In previous PV projects the strong PV supplier base in Asia has been a useful and valuable source of competitively priced intermediate products. On this point Asia's dominance in the PV industry is not just a curse for smaller-scaled new entrants in emerging PV regions. In various projects the supply base for intermediate products in Asia and China has been tapped in order to increase the competitiveness in the local and regional markets. This advantage can be improved further through trade legislation that exempts intermediate products from import duties.

Additionally, location-specific sourcing advantages might exist for other module components that are available in close proximity to the planned manufacturing site. The commercial benefits from local sourcing stem from shorter delivery times and reduced transportation costs. The increase in local value creation through spillover to regional supplier markets, e.g. multifilm laminate or aluminium profile producers, can result in broad-based public and political support for the industrial development initiative.

Local expertise in the production of key components can also contribute to the creation of regional market-entry barriers through product differentiation. The design of modules that are tailored to the climatic conditions of specific regions and applications is a trend that is expected to continue in the foreseeable future.

As already discussed, the investment case for the integrated downstream segment of the c-Si PV value chain depends largely on the terms and conditions upon which the PV supply chain is or will be accessed. The variation in the relative contribution to total costs in the low to upper sixties percentage range is a consequence of applying benchmark prices for major material cost drivers that lie within a range of ±15% around the median. The individual price points are heavily influenced by the scale and location of the individual reference project. Further markups for freight and insurance can skew the picture either way.

Depreciation costs are at an early stage, meaning that equipment depreciation has been fully taken into account. Capital expenditures have been benchmarked, at the low end, to Tier 1 operator investments and, at the high end, to turnkey production-line offerings. As can be seen in Fig. 9, charges related to the depletion of capital are the second-largest component, while labour is strongly dependent on the circumstances of the specific location. Labour intensity can be relatively high, especially compared with the upstream parts of the c-Si PV value chain.

The main contributors to total cost by type for the individual parts of the c-Si PV value chain have been presented in order to provide a better understanding of the various factors that drive production costs along the integrated value chain. Actual figures have not been published, as they are confidential and typically exhibit a wide range because of project-specific scaling, technology, product and procurement differences.

Empirical evidence suggests that a local production initiative only makes sense when flanked by a reasonably sized off-take market. This pull factor can lower market-entry barriers for new entrants and thereby contribute to high utilization rates in the early phases of the plant's life cycle.

Such an approach to realizing a project is especially suited to downstream plants, as these reach competitive economies of scale at lower nameplate capacities. These initial capacities can be adjusted to regional market needs and scaled up in accordance with market growth. Materials produced further upstream are likely to exceed local or regional market needs as a result of higher minimum capacity threshold levels: for these plants, additional distribution channels have to be established in export markets.

In a nutshell, the interest in local production is always tied to a strong PV installation market from which domestic stakeholders envision an increase in domestic value creation. The technology choice is usually part of the investigation, but in almost all instances it is biased towards c-Si technologies. This is a direct consequence of regional considerations, such as competitive advantages and product specification, as well as technology-specific reflections, such as maturity, industrial scale and project implementation risks. The operational risks are usually lower in the c-Si domain, especially if a new-entrant approach is followed.

Regional advantages in the upstream segment typically exist in countries where industrial electricity rates are low. As indicated in previous paragraphs, low rates can help to mitigate or even offset the disadvantages associated with established marginal producers that operate on a vastly depreciated asset basis.

On the surface, this line of argument might sound schizophrenic, as it promotes the usage of 'cheap' energy to manufacture a product that eventually will deliver energy at a higher cost. However, the general perception taken from conversations with decision makers boils down to the simple explanation that such a strategy fits into a transformative process in which these regions gradually step back from heavily subsidized electricity markets. It is therefore a precursor for a regime change where negative externalities from available hydrocarbon reserves are slowly internalized.

The local advantages for establishing a downstream cluster are usually found in high-volume regional end markets and, if viewed from an integrated perspective, in a secure and reasonably priced supply of silicon feedstock material. Regardless of the depth of vertical integration, a rigorous supply chain analysis can reveal significant levers in an investment case that is heavily influenced by sourcing conditions.

The extent to which an industrial development project should be flanked by accommodating legislation should be decided on a case-by-case basis. Instruments such as LCRs, import quotas and duties can protect an infant industry throughout its development phase. Nevertheless, such types of measure are most likely not in compliance with WTO agreements and, as such, have a high chance of being lambasted by trade partners with their own vested interest in the PV industry. On the other hand, it seems to be common practice to state that direct or indirect support should be granted to an industry which is sometimes regarded as a strategic asset. The next section gives a brief overview of the current trade dispute, and a review of trade strategies that are less prone to litigations.

Once the preconception that solar is expensive and at most a niche application in the global energy generation profile had been dispelled, many regions began to embrace the PV value proposition. A prospering regional end market is a necessary condition for the establishment of a local production cluster. The strength of the sufficient conditions is case specific and relates to the local supply chain, envisioned scale, capital expenditures and financing terms, as well as to the available labour pool. These areas must be investigated in a thorough due-diligence process in order to come up with a succinct decision as to whether and to what extent the state should resort to direct and indirect subsidies.

PV trade disputers

It is no coincidence that the protagonists of the global PV trade dispute are the three major economic zones, namely Europe, China and the USA. These regions have been at the forefront of the silicon electricity age and therefore have a vested interest in the production and deployment of solar power.

The over-capacity-induced price correction with marginal cost pricing led to allegations that certain regions engaged in exploitive trade practices. A cascade of formal complaints to the WTO and investigations by local trade bodies have prompted the imposition of various anti-dumping and countervailing duties (CVDs) in a tit-for-tat-like manner.

In international trade, dumping means that an exporter of a commodity persistently sets the international price below the domestic reference price. In national trade, dumping means that a manufacturer sells a commodity at a price below its production cost.

Because the drastic fall in prices of intermediate and final products in the PV market has been a function of over-capacity, a situation in which producers revert to marginal cost pricing, the argument for selling below total cost has never been too convincing. Moreover, the domestic market prices of poly-Si or PV modules were, in most instances, no higher than prices in the respective markets of the claimants. On the basis of this reasoning, the imposition of anti-dumping tariffs came as a surprise and leads to the conclusion that protective industry policies have the inherent risk of being confronted by an onslaught of unsubstantiated accusations.

The anti-subsidy investigation is another story, as there seems to be ample evidence that China utilized this instrument excessively in order to gain a competitive advantage in the renewable energy markets. Apart from the involvement of numerous state-owned enterprises, *indirect subsidies* are evident in the high gearing levels of top-tier manufacturers that in some instances receive financing on negative equity. In this case the imposition of CVDs is consequential and consistent with WTO rules, as one might legitimately claim that subsidies are one of the factors that have harmed the PV industry.

Typically, subsidies are part of the game of attracting investments and are used in the Western hemisphere too. The question is, up to what point are subsidies acceptable and not attacked by trade partners? Here, a balanced strategy has to be developed on a case-by-case basis, reverting to representative heuristics.

Finally, there needs to be a brief discussion of the effectiveness of LCRs, as these are popular instruments utilized by political decision makers to return portions of public funds to domestic manufacturers for the installation of renewable energy plants. LCRs are a directive to investors to source a certain quota of components from domestic suppliers. In the PV context these quotas are typically applicable to the power system, e.g. the scrapped regulation in Ontario that required a local content of 60% in renewable power projects in order to be eligible for attractive FiTs. Another commonly seen implementation of LCRs is in combination with public tenders in which bidders are obliged to adhere to certain local procurement requirements.

These regulations can be characterized as an indirect subsidy and are effectively a form of infant-industry protection. The motivations for implementing such regulations are manifold but generally founded on industrial development, job creation, know-how transfer, increased tax base and spillover to local academic R&D clusters.

Kunze et al. [2] presented empirical evidence that LCRs which are structured as financial subsidies (e.g. an FiT attached to an LCR) are more likely to be disputed than legislations that tie LCRs to bonuses or tendering systems (Fig. 10).

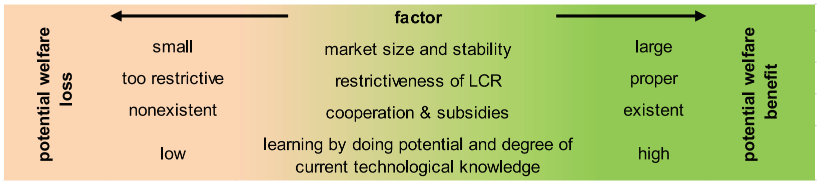


Figure 10. Empirical evidence of LCR effectiveness (Kunze et al. [2]).

"New entrants have various levers at their disposal for improving their competitive position in a low-margin but steadily growing industry."

Conclusion

Viridis.iQ GmbH is involved in various early stage assessments concerning the development of industrial PV production clusters. The experiences from these investigations are that new entrants have various levers at their disposal for improving their competitive position in a low-margin but steadily growing industry. These are not necessarily tied to subsidies and restrictive or opportunistic trade practices. Nevertheless, it needs to be acknowledged that industrial development and trade in the PV market is certainly far away from the purist Chicago School, and that certain protective industry measures should be made available in order to improve the chances of success of an industrial development in a sustainable long-term growth market.

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About the Author

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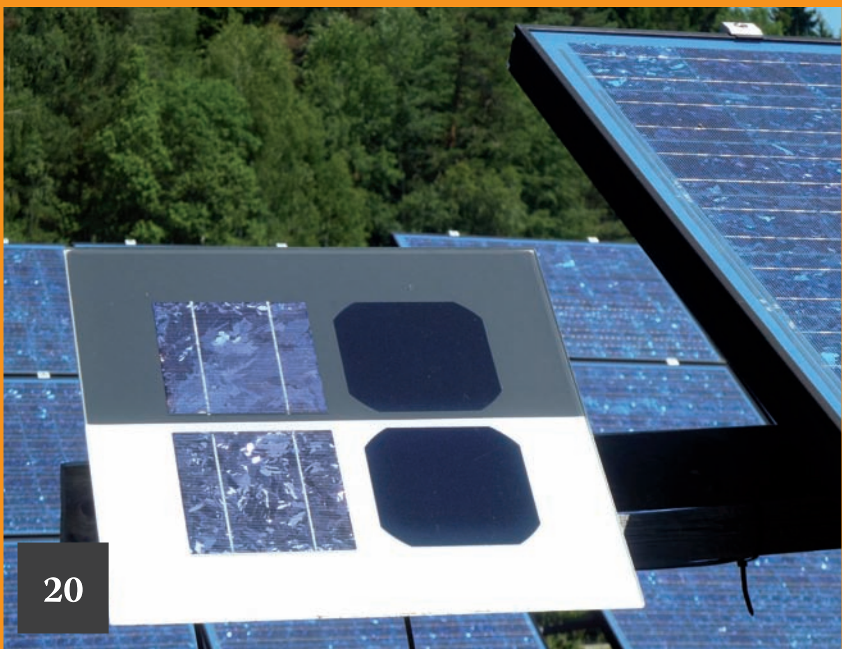
Materials



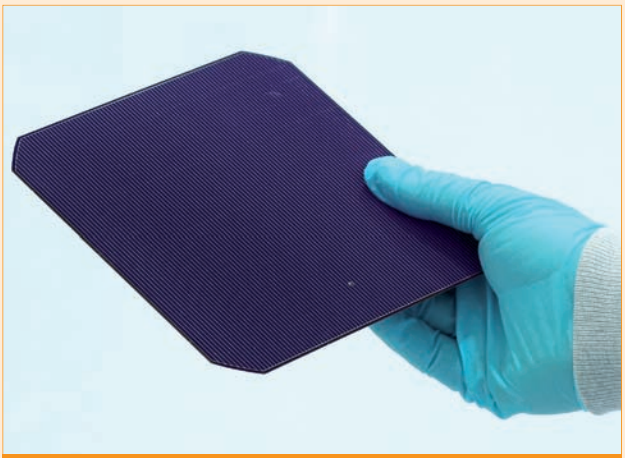
Meyer Burger and CSEM PV Center to establish heterojunction cell pilot line

Meyer Burger and CSEM PV Center are establishing the Swiss-Inno HJT Project that will include a pilot line and development programme to produce low-cost heterojunction silicon solar cell technology (HJT).

The Swiss-Inno HJT Project is being provided with around US$11.25 million over three years in R&D funding.

HJT development started in 2008 with Roth and Rau and the Photovoltaics Laboratory of the IMT at EPFL. The HJT project overall includes Meyer Burger group members Roth & Rau Research, PASAN and the Meyer Burger competence centre in Thun as well as CSEM's PV Center.

Key to the heterojunction technology is the deposition of ultra-thin layers of amorphous silicon on both sides of monocrystalline wafers. This offers bi-facial capabilities for higher conversion efficiencies.



Source: CSEM.

Meyer Burger and CSEM PV centre are to establish a heterojunction cell pilot line.

Research & Development

China Sunergy collaborates with UNSW on advanced hydrogenation technology

China Sunergy and the University of New South Wales, Australia (UNSW) are undertaking a five-year R&D programme to significantly improve solar wafer material quality using UNSW's advanced hydrogenation technology.

The agreement with China Sunergy will be operated through NewSouth Innovations, a wholly owned subsidiary of UNSW. UNSW has previously developed a process that employs hydrogen atoms to mask defects in multicrystalline wafers, boosting the electrical properties and providing higher cell conversion efficiencies.

Lower grade quality wafers could also be used without a negative impact on the material quality of the wafer and typical efficiencies achieved with higher quality wafers.

Finance & Results

GCL-Poly acquires controlling stake in Same Time electronics

Leading polysilicon and wafer manufacturer GCL-Poly is to become a majority shareholder in consumer electronics firm Same Time. Same Time, a printed circuit board specialist, is looking to use the share sale to GCL to refocus its business on solar, including plants and project development.

According to a Hong Kong Stock Exchange filing, GCL will pay HK$1.44 billion (US$186 million) for 360 million Same Time shares at HK$4 apiece. This represents 67.99% of Same Time's shares.

The directors of Same Time, based in Hong Kong, will resign from their posts once the deal is complete, and GCL-Poly will appoint a new board, according to the filing. GCL-Poly revealed to the Hong Kong Stock Exchange in October that it was planning an investment of HK$1.8 billion in Same Time.

Sino-American Silicon sales fall in January

Taiwan-based solar wafer producer, Sino-American Silicon (SAS), reported January 2014 sales of NT$1,834 million (US$60.6 million), down 10.31% on the previous quarter.

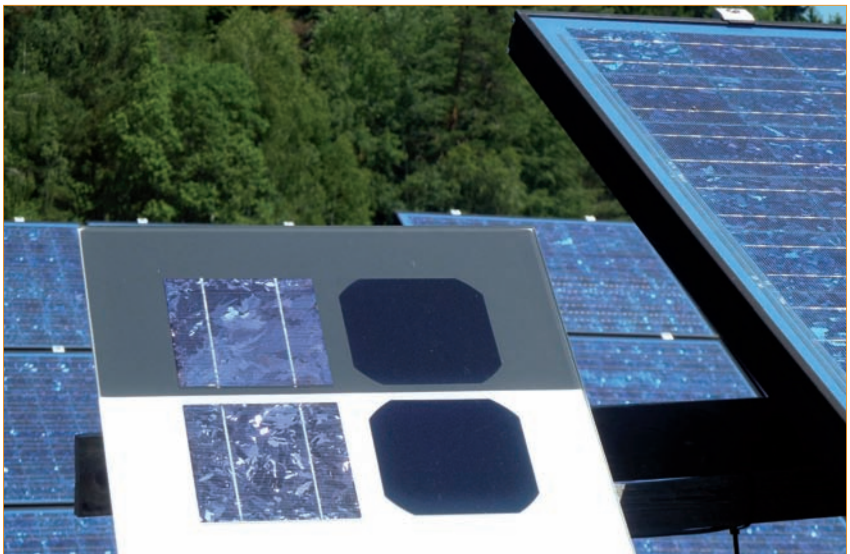
On a year-on-year basis, sales, which include subsidiary GlobalWafers, increased almost 13%. Sales had been relatively flat since mid-2013. The financial statement by the company does not provide insight into the reasons for the sales decline in January.

STR Holdings sales rebound

Specialist encapsulant supplier, STR Holdings, has said it expects fourth quarter 2013 sales to have slightly exceeded the prior quarter levels, indicating a reversal in its downward sales trajectory after losing First Solar as its major customer at the end of 2012.

STR Holdings guided fourth quarter sales to between approximately US$6.5 to US$6.7 million, compared to US$6.2 million in the prior quarter. Sales in the first quarter of 2013 had been US$11.2 million.

This would be the first sequential quarterly sales increase in nine quarters, according to the company. STR Holdings



Source: Wikicommons/Klaus Mueller.

Sino-American Silicon reported January 2014 down 10.31% on the previous quarter.

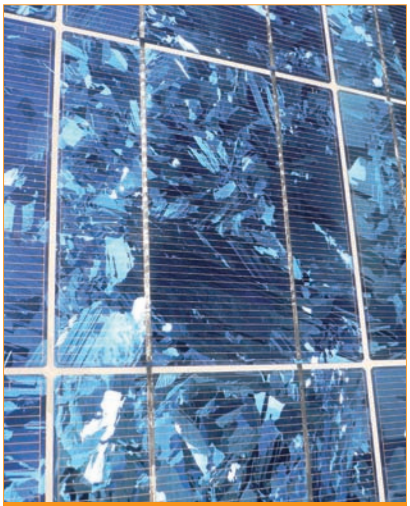
News

also guided EBITDA for the fourth quarter of 2013 to be in the range of US$3.4 million to US$3.9 million compared to US$4.6 million in the third quarter of 2013.

LDK Solar gains another extension to bondholder talks

LDK Solar said that a recent short extension to talks with bondholders that ended in February has been replaced with a new 21-day forbearance arrangement over unpaid interest on a US$280 million bond debt.

The company is continuing to engage with a majority of bondholders and has previously engaged with investment bank, Jefferies to act as a financial advisor in connection with the debt and LDK Solar's other offshore obligations. LDK Solar has not paid interest on the 'notes' since August 28, 2013.



Source: Georg Slickers.

Demand for polysilicon is expected to increase by 25% in 2014, says Solarbuzz.

Hemlock experienced higher polysilicon shipments in fourth quarter

Sales in the fourth quarter of 2013 at Dow Corning were boosted by higher polysilicon shipments from subsidiary, Hemlock Semiconductor.

Dow Corning said that customers purchased higher volumes of polysilicon in the quarter to meet annual contractual requirements.

However, Hemlock Semiconductor contributed a loss of US$26 million in the quarter, compared to an operating income of US$3 million in the third quarter of 2013, according to figures released by Dow Corning. This would translate into the worst performing quarter in the last two years in relation to the contribution to earnings to Corning of Hemlock.

Polysilicon demand

Polysilicon demand outpacing silicon per-watt reduction strategies

Polysilicon demand is increasing sharply on the back of expected global end market demand reaching 49GW in 2014, according to NPD Solarbuzz. The market research firm expects demand for polysilicon to increase by 25% in 2014, equivalent to a further 282,000MT required, which includes both solar and semiconductor demand.

Recently, Bernreuter Research reported that global polysilicon output in 2013 decreased to approximately 228,000MT, a 4% decline from 2012. Approximately 135,000MT of polysilicon production had been lost since 2011, due to prices falling below production costs on the back of major overcapacity and a large number of new entrants over the last five years.

Wacker and OCI grabbing polysilicon market share in China

The decision to penalise US polysilicon producers with heavy import duties by the Chinese Ministry of Commerce as part of the ongoing trade war has led to both Wacker and OCI grabbing further polysilicon market share in the country.

According to data provided by Bernreuter Research, which has been extracted from its most recent '2014 Who's Who of Solar Silicon Production' report, Germany-based Wacker Chemie increased its market share in China from 25% in 2012 to almost 33% in 2013.

Korean-based OCI was said to have increased its market share in China from 24% in 2012 to almost 28% in 2013.

Source: Hemlock Semiconductor.

Dow Corning's sales were boosted by higher polysilicon shipments from subsidiary, Hemlock Semiconductor.

Restructures

Wacker in €115 million windfall on polysilicon contract change

Major polysilicon producer, Wacker Chemie, said it would benefit from a one-time windfall of around €115 million in the first quarter of 2014 due to the restructuring of a supply contract with an undisclosed solar PV customer.

The company said that the restructured supply deal entailed adjustments to both delivery volumes and prices. The windfall was said to be due to recognising retained advance payments by the customer and from damages agreed. Wacker said that it would not disclose the customer's name and would keep the details of the new contract supply provisions confidential.

Daqo ramping polysilicon plant after removing bottlenecks

Daqo New Energy has completed the de-bottlenecking project at its polysilicon plant in Xinjian, China, which has started ramping to its expected nameplate capacity of 6,150MT.

The upgraded and decongested plant is expected to target production costs of around US$14/kg when fully ramped later in 2014.

Applied Materials continues downsizing of solar operations

In a continued effort to return its Energy and Environmental Solutions (EES) division to break even, despite two years of downsizing and restructuring, Applied Materials said it had reduced EES spending per quarter to US$25 million.

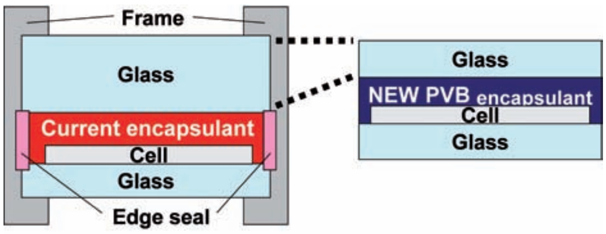
Applied Materials solar PV related equipment segment that includes screen printers and wire saw technologies is a segment with its EES division but also includes unrelated web coating tools.

According to its first fiscal quarter of 2014, Applied's EES sales were down 9% quarter-on-quarter to US$40 million. New order intake was said to have been US$40 million. Management noted in a call to discuss financial results that ESS was expected to more than double net sales in the second fiscal quarter, without providing further details.

The EES restructuring plan, which was initially discussed in March 2012, had a goal of lowering the division's annual revenue breakeven point to US$500 million by the end of its 2013 fiscal year. The continued downturn in capital spending due to chronic overcapacity across the supply chain meant that the company accelerated the downsizing though the last 12 months.

Product Reviews

Kuraray



Kuraray's new PVB film eliminates need for PV module edge seals

Product Outline: Kuraray, through joint research with the National Institute of Advanced Industrial Science and Technology (AIST) in Japan, has developed high-durability encapsulant polyvinyl butyral (PVB) films that are claimed to help make PV modules lighter and less expensive.

Problem: With the demand for PV modules rising, emphasis is being placed on improved reliability in harsh environments, lower installation burdens and better usability through lighter designs, as well as reduction in cost. Encapsulants for PV modules are materials used to encase or cover electrodes, wires and other (interior) components as well as the PV cells that generate electricity. They play the important role of protecting the interior from water and shocks while helping to keep output from degrading due to breakage and age.

Solution: Kuraray developed a high-strength, high-durability PV module encapsulant PVB film that can reduce costs and weight by simplifying the PV module structure by eliminating the need for using edge seals on the PV module to help stop water from leaking inside. Because of PVB's high modulus, the weight of the load is decreased, flex in the glass is reduced and the module's strength is maintained, while the simpler and lighter design saves costs.

Applications: PV module encapsulation.

Platform: 'TROSIFOL' was the world's first supplier of a special PVB film for PV applications. Its experience from the manufacture of PVB films for laminated safety glass gave rise to TROSIFOL SOLAR film, which can be processed both in vacuum laminators (single-stage process) and in the established two-stage process for laminated safety glass. The new PVB film is highly resistant to Potential Induced Degradation (PID).

Availability: Sampling in test markets undertaken since October 2013.

GCL-Poly

GCL-Poly's quasi-mono wafer 'G2' offers comparable performance to monocystalline

Product Outline: GCL-Poly Energy Holdings has started commercial mass production for its second-generation quasi-monocrystalline silicon wafer product. The GCL 'Monocrystalline G2' wafer is claimed to be comparable in conversion efficiencies with that of conventional Czochralski-based monocrystalline wafers.

Problem: Historically, the Czochralski-based method of producing monocrystalline solar wafers has production costs significantly higher than the casting techniques used to produce multicrystalline wafers. However, higher efficiencies and PID-free elements to monocrystalline have led to the developments of a quasi-mono technique.

Solution: According GCL-Poly, testing data provided by multiple clients using its new G2 wafers show the new wafers have produced an average increase of 1.1% in conversion efficiencies and a substantial improvement in silicon wafer performance compared to its first-generation monocrystalline silicon products launched in 2011.

Compared to monocrystalline wafers manufactured through the traditional ingot-pulling process, the company claims its G2 product delivers an additional 0.5% efficiency gain and a 1% average reduction in lumen degradation.

Applications: Quasi-mono wafers can be used for modules with output of 280/335W (60/72PCS) or above.

Platform: GCL-Poly developed the quasi-mono ingot furnace in-house that employs advanced casting techniques including a special polysilicon feed mechanism to produce the quasi-mono wafers from a casting technique that is said to create a unique crystalline structure.

Availability: Currently available.

Fab & Facilities

Materials

Cell Processing

Thin Film

PV Modules

Power Generation

Durable MWT PV modules made using silicone electrically conductive adhesive and an automated assembly line

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ABSTRACT

Metal wrap-through (MWT) module technology is an attractive approach for increasing module efficiency. This paper shares the results of MWT module fabrication using a silicone electrically conductive adhesive (ECA), a conductive backsheet (CBS) with a thin organic layer surface finish, and an automated module assembly line. Very low cell-to-module (CTM) power losses are observed, leading to a multicrystalline Si module power of 266W and a full-area efficiency of 16.8%. The modules are very stable in damp-heat conditions and thermal cycling, demonstrating minimal degradation after 1.5 × IEC requirements in terms of damp heat and thermal cycling, and well below 2% degradation after 2 × IEC requirements. These MWT modules have received IEC 61215 and IEC 61730 certification.

Introduction

Recent developments in the PV market have increased the need for high-efficiency crystalline Si PV module technologies. Many emerging high-efficiency technologies, however, tend to increase the complexity and cost of cell and module fabrication. The combination of metal wrap-through (MWT) cell technology and automated module assembly, based on a conductive backsheet (CBS) and electrically conductive adhesive (ECA), has the potential to reduce both overall complexity and cost/Wp. This paper describes the fabrication of such MWT modules using an automated module assembly line, and highlights the durability that can be achieved with this module concept when suitable materials are used.

Module concept

MWT cells [1] have front-side finger contacts which connect to the rear surface through vias in the Si wafers. As a result, the main contacts for both polarities are located at the rear of the solar cell. This structure leads to higher efficiency (lower shading losses) and lower Ag consumption than for traditional H-pattern solar cells.

Although it is possible to apply the traditional interconnection technology based on Cu ribbon soldering to MWT cells, the location of all contacts at the rear enables a more automated and simplified module build-up in which the components are added on top of each other [2] (Fig. 1). The assembly starts with a CBS: this backsheet has a metal foil laminated onto it, which has been patterned to create an interdigitated interconnection circuit. Small dots of ECA are printed onto the CBS using stencil printing; these dots are of the order of 1mm in diameter and there are more than 1000 of them on the foil. A perforated sheet of EVA is placed on the CBS so that the ECA dots are aligned with the holes in the EVA sheet, while keeping some spacing between the ECA and the EVA material. The cells are then put onto the CBS by a pick-and-place machine in such a way that the main electrodes at the rear are placed exactly on the ECA dots. A second sheet of EVA is then laid on the cells, followed by a glass sheet which will become the module's front cover.

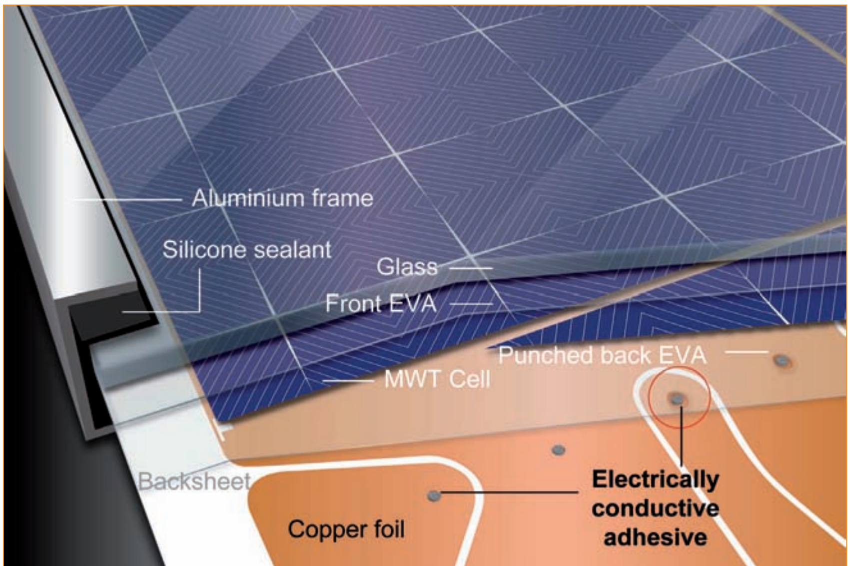


Figure 1. MWT module build-up.

"The location of all contacts at the rear enables a more automated and simplified module build-up."

The whole sandwich is then flipped to ensure that the glass is at the bottom, and introduced into a laminator for a conventional lamination cycle. During lamination, the EVA melts and fills all the empty spaces in the construct, including the space that had been left between the ECA and the edges of the holes in the EVA. The EVA and the ECA both cure during the lamination cycle. After lamination, the module is finished in the same way as a traditional module.

This module structure and build-up sequence has several advantages compared with traditional module assembly. Cell interconnection occurs in one go for all the cells through ECA curing during lamination, which enhances throughput. Moreover there is less manipulation of the cells and no local heating to very high temperatures as with soldering: as a result, the cells are subjected to less mechanical stress. This type of module assembly is therefore more suited to very thin cells, opening the way to lower Si wafer cost [3]. The large cross-section and the tapered shape of the Cu connectors ensure low cell-to-module (CTM) fill factor losses and further enhance module efficiency.

Experiments

Full-size (60-cell) modules were fabricated using an automated module assembly line from Eurotron (Fig. 2), located at Tianwei New Energy Factory in Chengdu, Sichuan Province, China. The line applies the different steps described above in an automated way. Multicrystalline MWT cells from Tianwei's cell manufacturing line were used; these were current matched, and all the cells in a module came from the same power class. The CBS featured a Cu foil, a white interlayer dielectric (ILD), and contact areas where the Cu foil was finished by a thin organic solderability preservative (OSP) layer. For the interconnection between the foil and the cells, a silicone-based ECA was used (see next section).

"Cell interconnection occurs in one go for all the cells through ECA curing during lamination, which enhances throughput."

After lamination, the modules were completed with the integration of junction boxes, bypass diodes and frames. The modules were measured the next day in a flash IV tester and by electroluminescence.

Modules from an initial manufacturing run were then placed in climate chambers to undergo accelerated ageing in damp heat conditions (85°C, 85% relative humidity) and thermal cycling (–40 to 85°C). The modules were removed from the climate chambers at regular intervals to monitor their performance and to compare measurements with those taken immediately before accelerated ageing. After the initial modules passed the standard requirements in terms of damp heat and thermal cycling, a new series of modules was prepared on the same line and in the same way, and sent to a testing company for IEC certification. In another MWT module production run, solar cells with a higher average efficiency were used, capitalizing on the progress in solar cell technology at Tianwei.

Silicone-based electrically conductive adhesives

ECAs are an emerging class of materials for PV modules [4]. The ECA is a critical component in the module structure described in previous sections: it must provide reliable contacts and adhesion during the entire lifetime of the module. Moreover, it has to be well suited to the selected application technique, cure completely during the encapsulant lamination cycle, and provide low resistivity and low contact resistance on a low-cost CBS.

Figure 2. Assembly line for the MWT modules used in the experiments.

There are various types of ECA, but most are based on an epoxy polymer matrix. Silicone polymers are another option, which are well suited to the application. Because of the very low glass transition temperature of silicone, it is possible to achieve soft but elastic properties of the ECA throughout the temperature range in which the PV module will operate [5]. These properties are expected to be favourable in the application, because excessive stress to the cells and joints caused by differences in expansion and contraction of the foil and the cells during thermal cycles is avoided. The rubbery state of the material provides stress relief, which is beneficial for durability. Silicone materials are also intrinsically durable owing to the strong Si–O chemical bonds in the polymer backbone.

"The ECA must provide reliable contacts and adhesion during the entire lifetime of the module."

The silicone-based ECA *Dow Corning®* PV-5802 was used for the experiments in this work. This ECA is a one-part metal-filled (but lead-free) paste that cures into a 'rubbery' yet highly conductive solid (resistivity < $4 \times 10^{-4} \Omega$cm) after a few minutes at 150°C. It has been designed to be compatible with OSP-covered Cu foils, providing good adhesion and low contact resistance on OSP-finished CBSs. As anticipated, the material showed a low elasticity modulus, even at freezing temperatures, in contrast to some organic ECAs (Fig. 3). Early tests with four-cell mini-modules had previously indicated that the behaviour of mini-modules using PV-5802 in thermal cycling was indeed outstanding, demonstrating a degradation of less than 1% after 600 thermal cycles [6].

Results and discussion

The modules produced as described above turned out to have a uniform high quality. The CTM power loss was very low (no higher than 0.3%); for many modules it was actually negative (which means that, going from cells to module, there was in fact a power *gain*). Although it varies depending on the specific module materials and module designs, the CTM power loss of traditional modules is typically of the order of several percentage points. Back-contact modules with CBSs often have a CTM power loss of around 1%. The fact that the present modules show an even lower CTM power loss of around 0% is attributed to the low contact resistance provided by the particular ECA that was used.

Illuminated *I-V* data for the modules in the second series are shown in Table 1; the data are for full-size (including frame) light-soaked modules, and measurements were taken at an independent testing institute. An average module power of 257.4W was obtained, and there was a narrow power distribution. Because of the low surface area of the modules compared with traditional modules (low spacing between cells and no bussing area), the efficiency is very high for industrial multicrystalline Si modules. The electroluminescence images were uniform and did not reveal any issues (Fig. 4).

In order to further enhance its PV module offering, Tianwei is continuously improving its solar cell technology. MWT technology enables cell efficiency gain to be directly translated into module power gain. Table 2 shows the results of more-recent modules that were made using cells with 17.8% average efficiency. For the best module, a maximum power of 266W was obtained, with again very low standard deviation; the corresponding efficiency of 16.8% is outstanding for an industrial-type multicrystalline module.

A good initial module performance is of course not sufficient to guarantee a high-quality PV product: the behaviour under accelerated ageing is at least as important. The results of damp-heat and thermal-cycling testing are shown in Figs. 5 and 6. It is immediately apparent that the modules comfortably pass the requirement of less than 5% degradation after 1000h of damp heat and 200 thermal cycles, as prescribed by IEC 61215. In fact, the observed

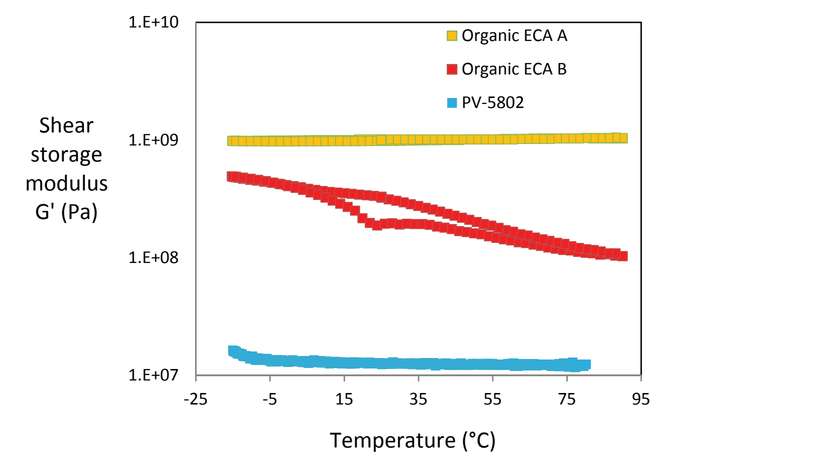


Figure 3. Dynamic mechanical analysis of three cured ECAs. Organic ECA A is very stiff throughout the operating temperature range. Organic ECA B has a strongly varying modulus depending on the temperature. Dow Corning PV-5802 demonstrates a low modulus throughout the entire relevant temperature range.

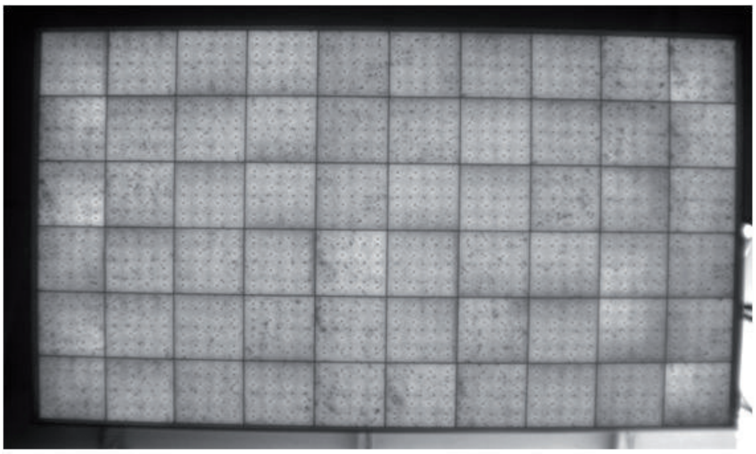


Figure 4. Electroluminescence image of an MWT module fabricated using a Cu-finished CBS and a silicone ECA, and on an automated module assembly line.

	V_{OC} [V]	I_{SC} [A]	*FF* [%]	Eff. [%]	P_{max} [W]
Average	37.62	9.12	75.0	16.2	257.4
Best module	37.61	9.11	75.3	**16.3**	258.1

Table 1. Illuminated *I-V* data for MWT modules (independently measured after light soaking; full-area efficiency; module area = 1.588m²).

	V_{OC} [V]	I_{SC} [A]	*FF* [%]	Eff. [%]	P_{max} [W]
Average	37.95	9.11	76.8	16.7	265.6
Best module	37.97	9.12	76.8	**16.8**	266.0

Table 2. Illuminated *I-V* data for MWT modules made using high-efficiency MWT multi-cells (internal measurement; full-area efficiency; module area = 1.588m²).

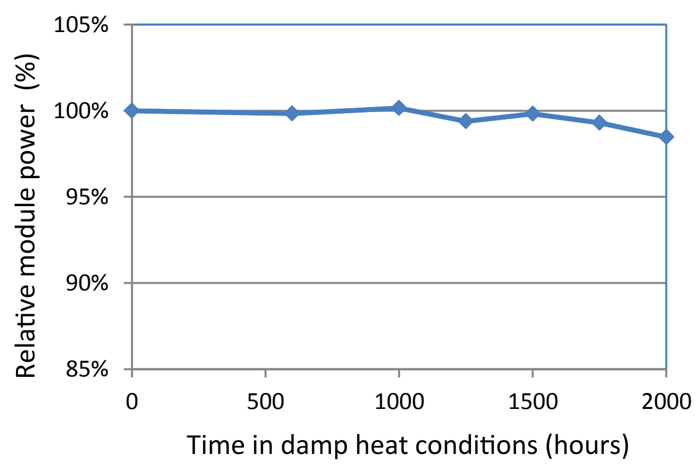


Figure 5. Relative power of an MWT module as a function of time in damp heat testing conditions (85°C, 85% relative humidity).

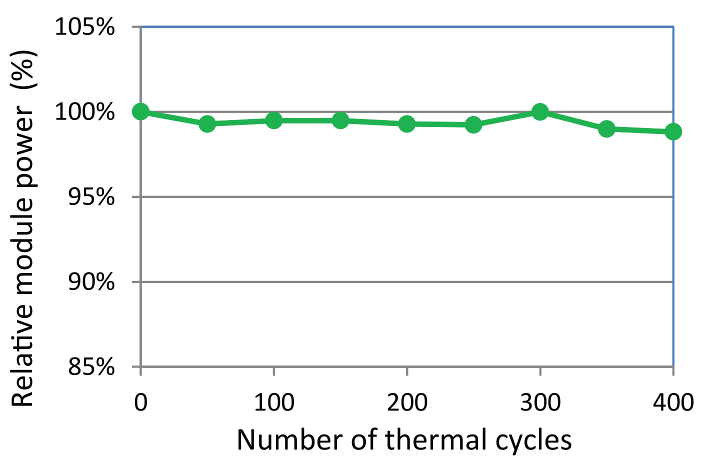


Figure 6. Relative power of an MWT module as a function of the number of thermal cycles (–40 to +85°C).

degradation after 1.5 × IEC requirements is still minimal, at well below 0.5%. There seems to be an onset of degradation from 1750h of damp heat, but it is still only 1.5% after 2000h.

As for thermal cycling, the degradation is 1.2% after 400 thermal cycles but a steady degradation does not yet appear to have kicked in. The overall conclusion is that the modules show excellent stability under extended accelerated ageing, which is evidence that the module assembly method and the bill of materials selected result in high-quality, highly durable modules.

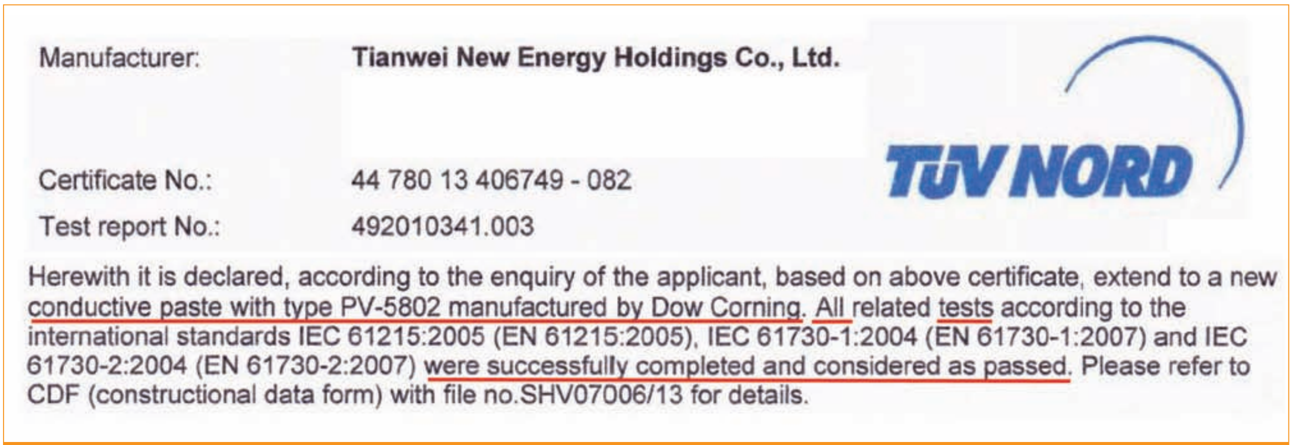
Consistently with these observations for the modules made in the initial run, the modules made afterwards, and which were sent to TUV Nord for IEC certification, behaved well in the various tests. As a result, the testing institution issued an official document certifying that this type of module with this bill of materials complies with the IEC61215 and IEC61730 requirements (Fig. 7).

The excellent durability observed for this type of module is equivalent to that of high-quality modules made using traditional cell and module technology. This is an important breakthrough for MWT module technology. On many occasions, doubts have been raised about the durability of MWT modules, and the scarce durability data available could only provide limited reassurance. The emergence of advanced materials specifically developed for the application, in combination with state-of-the art assembly equipment, is leading to a new phase in MWT technology deployment, where poor reliability is no longer a concern.

> "The modules degraded very little in accelerated ageing tests, comfortably passing IEC requirements."

Conclusion

The results of MWT module fabrication using a silicone ECA, an OSP-finished CBS and an automated MWT module assembly line have been presented. High-efficiency multicrystalline Si modules were obtained, with a power of up to 266W and an efficiency of 16.8% thanks to low CTM power losses. The modules degraded very little in


Manufacturer: Tianwei New Energy Holdings Co., Ltd.

Certificate No.: 44 780 13 406749 - 082

Test report No.: 492010341.003

Herewith it is declared, according to the enquiry of the applicant, based on above certificate, extend to a new conductive paste with type PV-5802 manufactured by Dow Corning. All related tests according to the international standards IEC 61215:2005 (EN 61215:2005), IEC 61730-1:2004 (EN 61730-1:2007) and IEC 61730-2:2004 (EN 61730-2:2007) were successfully completed and considered as passed. Please refer to CDF (constructional data form) with file no.SHV07006/13 for details.

Figure 7. Excerpt of the certificate for the MWT modules fabricated using an automated module assembly, a CBS with OSP-finished Cu foil, and a silicone ECA.

accelerated ageing tests, comfortably passing IEC requirements, and with degradation well below 2% after 2 × IEC requirements. Another set of modules was sent to an external testing company and passed all the tests: as a result, an IEC 61215 and IEC 61730 certificate was delivered for this type of module.

Acknowledgements
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About the Authors


Hongfeng Lin is vice CTO and director of the R&D centre at Tianwei New Energy Holdings Co., Ltd., China, and has extensive experience in developing technologies for crystalline silicon PV applications. He received his Ph.D. in semiconductor physics from Lanzhou University.


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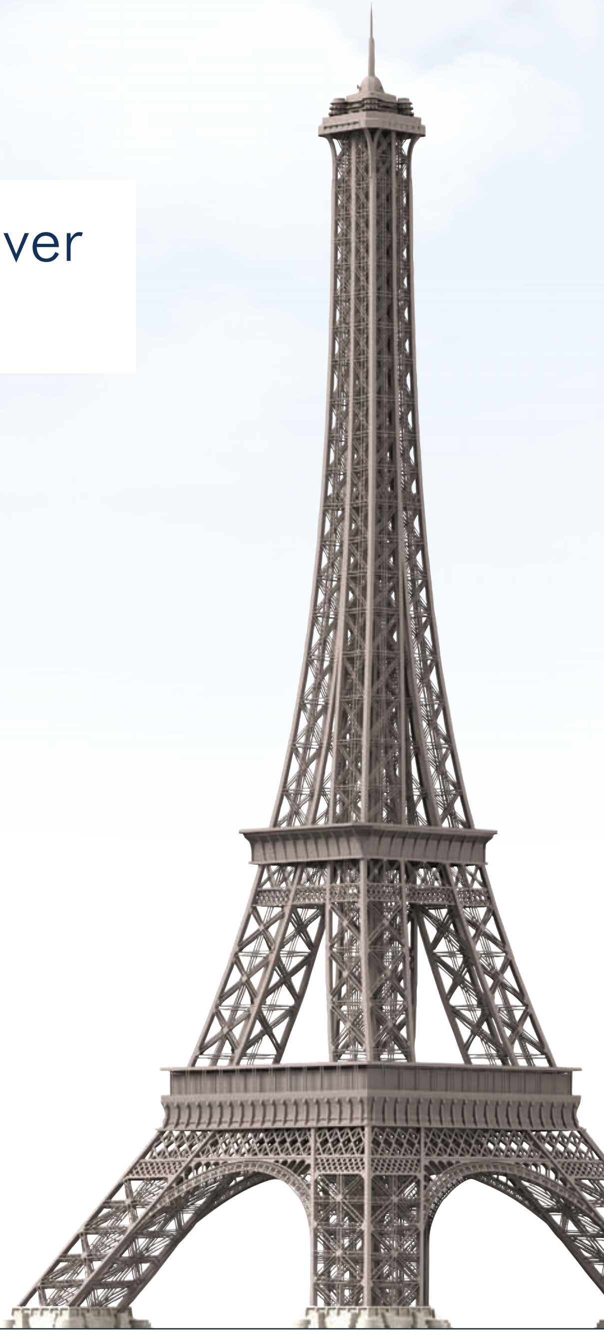

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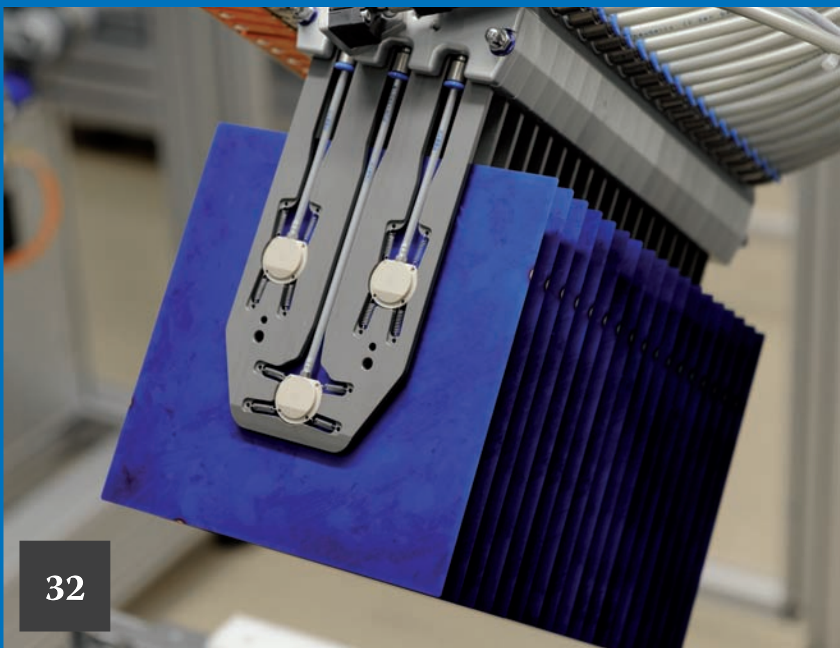
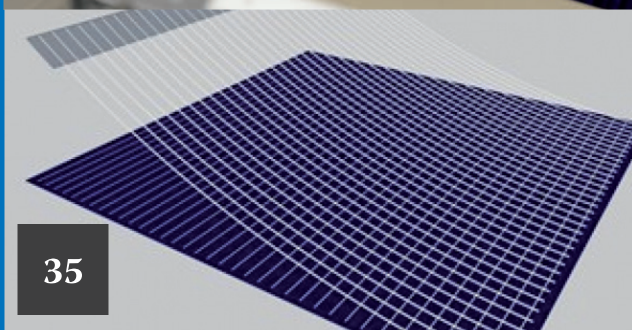
Cell Processing

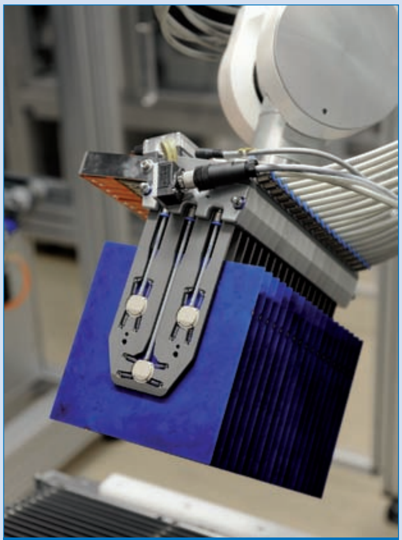




News

US trade case could see American factories make 'Chinese' solar products

The latest solar trade case brought in the US could see American companies produce "Chinese" solar products, if the petitioner SolarWorld's terms were met, according to a lawyer representing Chinese PV manufacturers. At present, the country of origin of a module is defined by where the cell is produced. SolarWorld is unhappy that Chinese firms are able to use Taiwanese cells in their modules and circumvent US trade duties on panels from China in the process. SolarWorld wants the origin of a module to be based on a 'two out of three' rule where location of wafer production, cell and module assembly are all considered.



Source: SolarWorld.

US companies could end up making 'Chinese' cells if SolarWorld's petition in America is upheld.

Financial News

Screen printing firm DEK sold to ASM Pacific Technology for US$170 million

Manufacturer of PV screen printing equipment, DEK Solar, has been sold as part of a deal between the owner of DEK, Dover Corporation, and ASM Pacific Technology (ASMPT), itself a part of Dutch-based semiconductor equipment supplier ASM International.

According to a Hong Kong Stock Exchange filing by ASMPT the acquisition of DEK from Dover was put at US$170 million. ASMPT said in a separate press release that DEK had revenue of US$167 million in 2012 and over 700 employees worldwide.

Applied Materials continues downsizing of solar operations

In a continued effort to return its Energy and Environmental Solutions (EES) division to breakeven, despite two-years of downsizing and restructuring, Applied Materials said it had reduced EES spending per quarter to US$25 million.

Applied Materials solar PV related equipment segment that includes screen printers and wire saw technologies is a segment within its EES division but also includes unrelated web coating tools.

According to its first fiscal quarter of 2014, Applied's EES sales were down 9% quarter-on-quarter to US$40 million. New order intake was said to have been US$40 million.

SunPower nearly doubling capital expenditure in 2014

SunPower has guided capital expenditure (capex) plans for 2014 that are nearly double spending in 2013.

SunPower reported in its 2013 annual report that capex would be in the range of US$150 million to US$170 million in 2014, a possible increase of 88.8% from its 2013 guidance range of US$70 million to US$90 million.

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

The company is expected to be capacity constrained throughout 2014, unless further expansion is made at its JV Fab 3 in Malaysia, which was reported to have a production capacity of 800MW but a nameplate capacity over 1GW.

Neo Solar Power reports 12 consecutive months of revenue growth

At the beginning of January, Neo Solar Power (NSP), a major merchant solar cell and module manufacturer based in Taiwan reported its twelfth consecutive month of revenue growth.

The company reported revenue for December 2013 of NT$2,406 million (US$80.1 million), up from NT$2,333 million in the previous month, a new record high for the year. Total revenue for NSP in 2013 was NT$20,092 million (US$669.5 million).

The company has benefited from increased outsourcing of solar cells by Chinese customers circumventing anti-dumping duties in the US as well as increased solar cell and module outsourcing from major Japanese PV manufacturers to meet demand in the Japanese domestic market.

Efficiencies

Fraunhofer ISE develops 24% low-cost n-type solar cell with TOPCon passivation

In late November 2013, Fraunhofer ISE said it had developed a low-cost rear contact Tunnel Oxide Passivated Contact 'TOPCon' n-Type solar cell that achieved a conversion efficiency of 24%.

According to Fraunhofer ISE TOPCon provides a passivated contact across the entire rear surface of the cell, while achieving improved surface passivation, reducing resistance losses. The research centre noted that a key hurdle in reaching high efficiencies with n-type wafer/cells is the patterning scheme of the rear contact as the rear side metal contacts are an efficiency limiting factor.

The TOPCon cell was said to provide a simple rear contact without any patterning required, reducing costs and process complexity.

Silicon efficiency breakthrough awarded UK research prize

An Australian engineer has been awarded £300,000 (US$493,000) by the UK's Institution of Engineering and Technology (IET) for his work on increasing the efficiency of solar PV whilst lowering costs.

Professor Stuart Wenham from the University of New South Wales (UNSW) was awarded the prestigious A F Harvey Engineering Research Prize after he created a mechanism for controlling hydrogen atoms.

The mechanism allows the team to correct deficiencies in silicon – the most expensive component of a solar cell. By correcting deficiencies, lower quality silicon is able to outperform solar cells that have been made from higher quality materials.

DuPont touts cell efficiency gains with REC Solar

DuPont Microcircuit Materials has said that its 'Solamet' PV18x series metallization pastes have been instrumental in raising REC Solar's multicrystalline modules' peak power performance (Pmax(Wp)) to new record levels.

DuPont noted that it had been collaborating with REC Solar on metallization paste optimisation since operations at REC's state-of-the-art manufacturing facility in Singapore started in 2010. REC has previously reported in financial statements that it was focusing on reducing losses due to absorption in front and rear solar cell layers and thereby increasing cell voltage.

The focus on front-side cell improvements had contributed to increased cell efficiencies. The company had reported that average multicrystalline solar cell efficiencies at its Singapore plant had reached 17.1% across all production lines in 2012, up from 16.8% in 2011.

German R&D project reports record PERC solar module performance

The first R&D project that took three years to complete as part of the German Photovoltaics Innovation Alliance has reported a world record for a PERC (Passivated Emitter and Rear Cell) solar module of 306 Watts (60-cell format).

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Orders and agreements

Meyer Berger to supply South American PV production line

Semiconductor technology group, Meyer Berger has announced an order from a European customer to provide CHF10 million (US$11 million) worth of components for a PV production line in South America.

The wafer and cell equipment is for a monocrystalline silicon ingot to solar module production line.

A contract has been signed and delivery is scheduled for the second half of 2014. The production facility will have an annual production of 70MW to help supply the country's energy needs.

Despatch Industries to use Kromax as sales rep in China and Taiwan

Specialist PV equipment supplier, Despatch Industries has signed an exclusive sales and service agent agreement with Kromax International for China and Taiwan markets. Ellen Cheng, Despatch Industries' China and Taiwan regional general manager said: "Kromax has experience in the solar industry and an extensive sales and service team. Our partnership allows us to leverage Kromax's large network in the China and Taiwan region and further our presence and brand in the solar equipment market." Kromax is said to have offices in Taiwan, China and Southeast Asia and a team of more than 100 engineers.

Centrotherm received orders worth €30 million

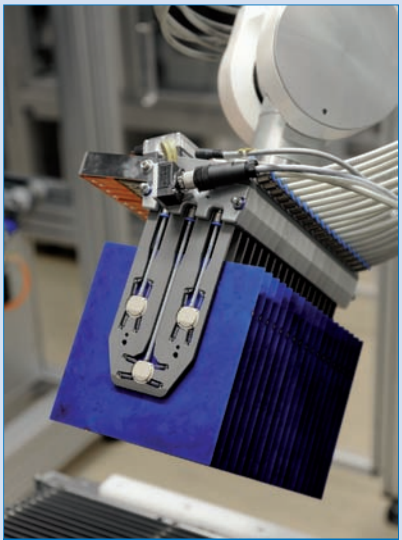
PV equipment supplier, centrotherm, said that in December 2013 and January 2014 new order intake had totalled around €30 million.

The company also noted that its "single equipment" order backlog stood at around €62 million. The recovery in orders was said to be related to a wide-range of equipment packages for customers expanding existing lines as well as the establishment of new production lines for both solar cell and module production.

The company noted that expansion plans were noticeable for customers in Japan and the US, due to customers running at full capacity.

US trade case could see American factories make 'Chinese' solar products

The latest solar trade case brought in the US could see American companies produce "Chinese" solar products, if the petitioner SolarWorld's terms were met, according to a lawyer representing Chinese PV manufacturers. At present, the country of origin of a module is defined by where the cell is produced. SolarWorld is unhappy that Chinese firms are able to use Taiwanese cells in their modules and circumvent US trade duties on panels from China in the process. SolarWorld wants the origin of a module to be based on a 'two out of three' rule where location of wafer production, cell and module assembly are all considered.



Source: SolarWorld.

US companies could end up making 'Chinese' cells if SolarWorld's petition in America is upheld.

Financial News

Screen printing firm DEK sold to ASM Pacific Technology for US$170 million

Manufacturer of PV screen printing equipment, DEK Solar, has been sold as part of a deal between the owner of DEK, Dover Corporation, and ASM Pacific Technology (ASMPT), itself a part of Dutch-based semiconductor equipment supplier ASM International.

According to a Hong Kong Stock Exchange filing by ASMPT the acquisition of DEK from Dover was put at US$170 million. ASMPT said in a separate press release that DEK had revenue of US$167 million in 2012 and over 700 employees worldwide.

Applied Materials continues downsizing of solar operations

In a continued effort to return its Energy and Environmental Solutions (EES) division to breakeven, despite two-years of downsizing and restructuring, Applied Materials said it had reduced EES spending per quarter to US$25 million.

Applied Materials solar PV related equipment segment that includes screen printers and wire saw technologies is a segment within its EES division but also includes unrelated web coating tools.

According to its first fiscal quarter of 2014, Applied's EES sales were down 9% quarter-on-quarter to US$40 million. New order intake was said to have been US$40 million.

SunPower nearly doubling capital expenditure in 2014

SunPower has guided capital expenditure (capex) plans for 2014 that are nearly double spending in 2013.

SunPower reported in its 2013 annual report that capex would be in the range of US$150 million to US$170 million in 2014, a possible increase of 88.8% from its 2013 guidance range of US$70 million to US$90 million.

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

The company is expected to be capacity constrained throughout 2014, unless further expansion is made at its JV Fab 3 in Malaysia, which was reported to have a production capacity of 800MW but a nameplate capacity over 1GW.

Neo Solar Power reports 12 consecutive months of revenue growth

At the beginning of January, Neo Solar Power (NSP), a major merchant solar cell and module manufacturer based in Taiwan reported its twelfth consecutive month of revenue growth.

The company reported revenue for December 2013 of NT$2,406 million (US$80.1 million), up from NT$2,333 million in the previous month, a new record high for the year. Total revenue for NSP in 2013 was NT$20,092 million (US$669.5 million).

The company has benefited from increased outsourcing of solar cells by Chinese customers circumventing anti-dumping duties in the US as well as increased solar cell and module outsourcing from major Japanese PV manufacturers to meet demand in the Japanese domestic market.

Efficiencies

Fraunhofer ISE develops 24% low-cost n-type solar cell with TOPCon passivation

In late November 2013, Fraunhofer ISE said it had developed a low-cost rear contact Tunnel Oxide Passivated Contact 'TOPCon' n-Type solar cell that achieved a conversion efficiency of 24%.

According to Fraunhofer ISE TOPCon provides a passivated contact across the entire rear surface of the cell, while achieving improved surface passivation, reducing resistance losses. The research centre noted that a key hurdle in reaching high efficiencies with n-type wafer/cells is the patterning scheme of the rear contact as the rear side metal contacts are an efficiency limiting factor.

The TOPCon cell was said to provide a simple rear contact without any patterning required, reducing costs and process complexity.

Silicon efficiency breakthrough awarded UK research prize

An Australian engineer has been awarded £300,000 (US$493,000) by the UK's Institution of Engineering and Technology (IET) for his work on increasing the efficiency of solar PV whilst lowering costs.

Professor Stuart Wenham from the University of New South Wales (UNSW) was awarded the prestigious A F Harvey Engineering Research Prize after he created a mechanism for controlling hydrogen atoms.

The mechanism allows the team to correct deficiencies in silicon – the most expensive component of a solar cell. By correcting deficiencies, lower quality silicon is able to outperform solar cells that have been made from higher quality materials.

DuPont touts cell efficiency gains with REC Solar

DuPont Microcircuit Materials has said that its 'Solamet' PV18x series metallization pastes have been instrumental in raising REC Solar's multicrystalline modules' peak power performance (Pmax(Wp)) to new record levels.

DuPont noted that it had been collaborating with REC Solar on metallization paste optimisation since operations at REC's state-of-the-art manufacturing facility in Singapore started in 2010. REC has previously reported in financial statements that it was focusing on reducing losses due to absorption in front and rear solar cell layers and thereby increasing cell voltage.

The focus on front-side cell improvements had contributed to increased cell efficiencies. The company had reported that average multicrystalline solar cell efficiencies at its Singapore plant had reached 17.1% across all production lines in 2012, up from 16.8% in 2011.

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Product Reviews

Centrotherm

Centrotherm offers flexible metallization options on c.FIRE platform

Product Outline: Centrotherm photovoltaics has upgraded its c.FIRE fast firing furnace to enable PV solar cell manufacturers to optimally configure 'burning out' and 'sintering' of solar cell metal contacts through selecting various option packages.

Problem: The use of a wide variety of metallization pastes available for a host of cell designs and characteristics means that maximum process security as well as excellent yields in the shortest operating times, PV solar cell manufacturers need a fast firing furnace that has flexible processing parameters.

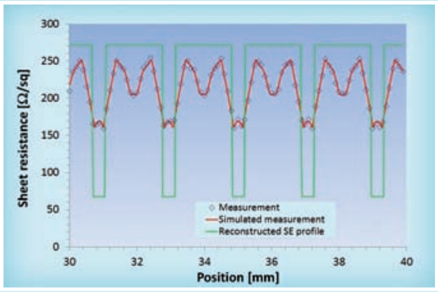
Solution: Solar cell manufacturers can optimally configure c.FIRE for their specific process and production requirements having excellent temperature homogeneity and process stability, c.FIRE also has a throughput of more than 4,300wph, while being able to use standard market as well as newly developed metallization pastes.
With its low pressure tube furnace for diffusion, centrotherm claims improved homogeneity at emitter resistances of up to 150 Ω/square, thereby enabling the efficiency potentials of conventional, and especially new metallization pastes to be exploited (emitter resistance > 100 Ω/square).

Applications: Firing of front side metallization and alloying of rear side contact.

Platform: The firing zone is equipped with short wave infrared light elements that deliver optimum results in terms of useful life, as well as process flexibility and results.
A VOC (Volatile Organic Compound) handling system consisting of a condenser and electrostatic filter has been fully integrated into the housing and ensures the reliable and energy efficient separation of the solvents released during the drying process.

Availability: Currently available.

Sheet resistance



Sheet resistance measurement of Selective Emitters offered in Sherescan 2.0

Product Outline: Sunlab has introduced upgrade to the Sherescan 2.0. The new version of the free to download software enables measurement of sheet resistances of selective emitter (SE) structures.

Problem: Four-point probes (4PP) can be used to measure sheet resistances, in a calibration-free sense. These measurements are carried out on (diffused) wafers. However, when the sheet resistance varies strongly within distances that are comparable with the size of the 4PP, no useful, spatially resolved sheet resistance information can be obtained. This problem also occurs in case of Selective Emitters.

Solution: Sherescan 2.0 comes with a smart SE algorithm that derives from raw measurement data, sheet resistance values of the highly and lowly doped zones of the SE. The measurements can be done in both finger and busbar areas, for half-fabricates with an arbitrary number of fingers and busbars. The outcome is a block-profile representing low-high sheet resistance values of de SE as well as the sizes of the zones.

Applications: In the lab: Optimization of the SE process. In the fab: Sherescan 2.0 can be used as a 'next-to-line' tool for quality control of the SE process. It gives information of spread in sheet resistance values and inhomogeneities, e.g. in diffusion and etch depths.
In-line SE equipment sometimes contains SE measurement in an indirect sense and therefore requires calibration. Moreover, these measurements are confined to a limited area. Sherescan 2.0 can validate built-in (indirect) SE measurements and allows measurement everywhere on the wafer.

Platform: The Sherescan has been upgraded to version 2.0. SE measurement spots can be defined in an intuitive way by clicking on a solar-cell map. License for Selective Emitter measurement functionality can be purchased.

Availability: Software is freely downloadable and currently available.

Low-cost, high-efficiency solar cells for the future: ISC Konstanz's technology zoo

Joris Libal, **Valentin D. Mihailetchi** & **Radovan Kopecek**, ISC Konstanz, Konstanz, Germany

ABSTRACT

After several years of crisis, the PV manufacturing industry is expected to pick up again from 2014 onwards, and cell and module producers will consequently expand their production capacities in the coming years. To obtain high margins, producers must introduce new products that are better performing in terms of electrical performance and lifetime, even under harsh climatic conditions (e.g. in desert regions). This requires the use of innovative technologies that not only allow low production costs (US$/Wp), but also guarantee at the same time high module efficiencies and – even more importantly – high energy yields in terms of kWh over the entire lifetime of the system. This means that the most promising advanced cell concepts will use a limited number of standard industrial process steps and proven standard equipment. For at least the next five (probably more) years, high efficiency (>20%) at a reasonable cost will still be achieved with crystalline silicon-based technology alone. The research and development at ISC Konstanz therefore concentrates mainly on cell concepts that can be implemented using standard tube furnace diffusions and screen-printed metallization, with a focus on n-type-based technologies. This paper gives an overview of ISC Konstanz's technology zoo, including BiSoN, PELICAN and ZEBRA cell concepts, which are ready for industrial implementation. In addition, the integration of these innovative cells into modules, along with the importance of various features – such as bifaciality – in increasing the energy yield, is discussed.

Introduction

During the past three years the PV market has been extremely dynamic. On the one hand, module prices fell very quickly, making PV systems unexpectedly cost effective; on the other hand, the solar cell and module manufacturers fought for survival in the consolidating market, allowing prices to drop even faster – often even below production costs. Many companies became insolvent during this period, while some of the large ones stepped out of the business because of, for example, large losses and low expected margins in future sales. This hectic situation has slightly improved since the end of 2013, and PV producers in the cell and module sector are starting to realize profits once more.

During this long PV crisis, the main focus of the cell and module manufacturers was survival, by making their standard p-type c-Si products highly efficient and cost effective; many manufacturers were not willing to invest in novel technologies, although some of them have taken a small step forwards, implementing passivated-emitter-and-rear-cell (PERC) or metal-wrap-through (MWT) devices – concepts that are still based on monofacial p-type technology. A good overview of these technologies is given by Mack et al. [1].

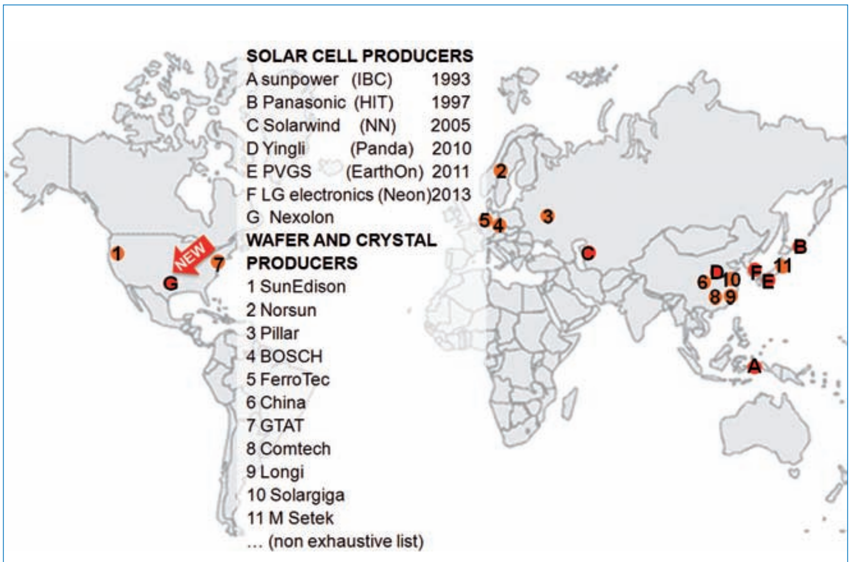


Figure 1. The major n-type solar cell and wafer manufacturers on the PV market in 2013.

The situation is currently changing, as innovations are now extremely important for the future ability of the still-existing companies to face competition on the market. The Chinese government is supporting this innovative spirit: efficiency limits have been set for new companies entering the market if they want to obtain governmental support. In addition, the current high balance of system (BOS) costs show very clearly that increased module efficiencies are necessary in order to make the whole PV system more cost effective, given the savings that have been realized on material and installation (i.e. area-related) costs from the BOS. This means that, in order to further reduce the system cost, the efficiency of solar cells must not be compromised by cheaper processes: consequently, the future is in the highest efficiency devices, mainly based on n-type c-Si technologies. Fig. 1 shows the worldwide distribution of n-type cell and wafer manufacturers on the market in 2013, along with the new ones that are just entering; it is expected that many others will follow in the next few years. These n-type technologies are scheduled to be discussed at the 2014 4th nPV Workshop in 's-Hertogenbosch (www.nPV-workshop.com).

> “The future is in the highest efficiency devices, mainly based on n-type c-Si technologies.”

Another important technological benefit of n-type devices is that most of them are bifacial. Since module manufacturers are moving towards glass–glass modules anyway, the electricity harvest of a system can be drastically enhanced by using bifacial cells in such modules. Different bifacial technologies and the need for standardization in this area are topics for discussion at the 2014 2nd bifi PV Workshop in Chambéry (www.bifiPV-workshop.com).

Industrial solar cell concepts at ISC Konstanz

Many, if not all, solar cell manufacturers have very similar roadmaps to that of ISC Konstanz, as depicted in Fig. 2. In recent years ISC has developed solar cell concepts based on standard p-type c-Si technology with several structures and properties, as well as more advanced concepts based on n-type Si wafers. In order to categorize the solar cell concepts forming ISC Konstanz’s technology zoo, names such as PELICAN, BiSoN, MoSoN and ZEBRA have been given to the different technologies. The efficiencies indicated in black in Fig. 2 show the current status, while those in white indicate the reasonable goals for 2014.

The idea behind this roadmap is to be able to offer upgrades to every c-Si solar cell producer, no matter how far advanced it is with the technology in its production line. For example, if a ‘standard solar cell producer’ wants to upgrade to PERC, then PELICAN can be offered; if a p-type PERC producer would like to change to n-type technology, the most straightforward step would be to switch via MoSoN to BiSoN technology, gaining experience first with n-type substrates and B diffusion, and then with rear passivation and rear open contacts. The end of the roadmap – so far – is the n-type bifacial ZEBRA IBC (interdigitated back contact) technology, with the potential for efficiencies greater than 23% with diffused and greater than 24% with ion-implanted regions.

The parameters and corresponding references are summarized in Table 1. Compared with p-type, n-type concepts are better performing, since the n-type substrates not only have better properties (such as no light-induced degradation – LID – and better tolerance for prominent metallic impurities), but also show less degradation and are therefore more suitable for high-temperature processes, such as B diffusion. Other advantages of n-type concepts are summarized in Kopecek & Libal [2].

All ISC Konstanz technologies are based on standard industrial PV technology: c-Si 6″ wafers, tube furnace diffusions, passivations with different dielectrics and screen printing of metal contacts. Existing solar cell lines can therefore be upgraded for fabrication of the more advanced solar cell concepts just by including some additional (standard) equipment. In the case of PELICAN, MoSoN and ZEBRA, apart from some additional plasma-enhanced chemical vapour deposition (PECVD) capacity, a laser system for the ablation of dielectrics is needed. The processes are optimized, and industrially viable cleaning steps are selected and developed, since for high-efficiency devices the surfaces have to be very clean prior to the processing steps, such as B diffusion, P diffusion and passivation. The additional processes make the

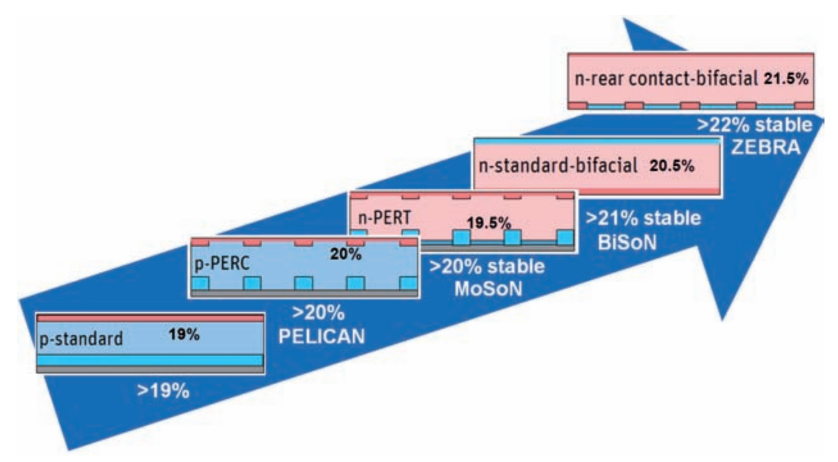


Figure 2. Roadmap of ISC Konstanz in regard to the different solar cell technologies and their efficiencies.

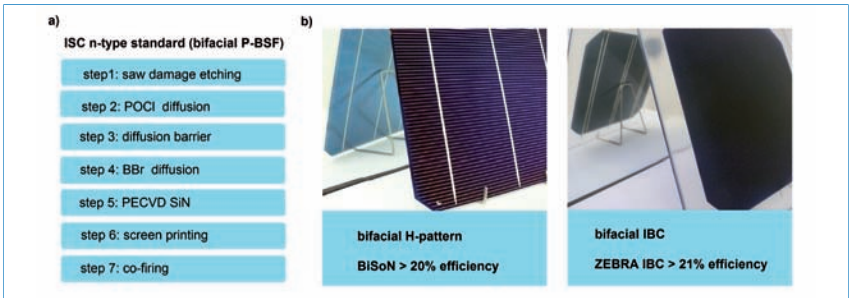


Figure 3. (a) BiSoN cell process flow; (b) photographs of bifacial BiSoN and ZEBRA cells.

Technology	Type	Area [cm²]	*FF* [%]	J_{sc} [mA/cm²]	V_{oc} [mV]	η [%]	η_{ave} [%]
Standard	p-type full Al	239	79.1	37.7	645	19.2	19.0
PELICAN	Cz-PERC full Al	239	80.1	38.1	653	19.9	19.8
MoSoN	n-PERT full Al	239	77.4	38.2	658	19.5	19.3
BiSoN	n-PERT bifacial	239	78.9	39.4	652	20.3*	20.0
ZEBRA	IBC bifacial	239	78.5	41.9	649	21.3	21.0

*confirmed by Fraunhofer ISE CalLab.

Table 1. Low-cost solar cells on 6″ wafers with industrial processes realized at ISC Konstanz.

fabrication more costly in terms of US$/cell; however, the cost of ownership (COO) calculations (summarized in the section 'Cost of ownership') show that the cell processes discussed here pay off in terms of US$/Wp at the module level, leading to even higher benefits at the system level (as discussed in the section 'Future systems'). Fig. 3 shows, as an example, the simplicity of the BiSoN process and photographs of the bifacial BiSoN and ZEBRA n-type solar cells.

Materials

Wafer

The worldwide distribution map in Fig.1 illustrates the increasing number of manufacturers which produce n-type wafers on an industrial scale. The wafer represents the most significant item of the cell production cost: it still remains a particular challenge to procure n-type wafers at a price which is comparable with that of p-type wafers. One reason why the production cost for n-type Si crystals is higher than for p-type is the lack of economy of scale in the case of n-type owing to the few cell manufacturers using n-type. Another factor that can potentially lead to an increased cost for n-type wafers is the high segregation coefficient of phosphorus (n-type dopant), which leads to a larger resistivity range over the crystal. For solar cell architectures that require a narrow resistivity range, the wafer yield can be significantly reduced. To resolve this issue, continuous Cz-pulling techniques have been developed, such as CCZ-Si by Sunedison, in which crystals grown using the CCZ-Si technique feature a narrow resistivity range for both p- and n-type. In addition, this technique is more cost effective than standard batch-type Cz-Si, because of the cost savings for consumable parts of the pullers (for details see Kearns [3]). Consequently, the CCZ-technique leads to a reduction in costs for high-quality p-type Cz-Si wafers as well.

> "The ZEBRA cell concept demonstrates constant high efficiencies for wafer resistivities between 3 and 14Ωcm."

Regarding n-type, another possibility for avoiding a potential yield loss due to a wide resistivity distribution is to develop cell concepts that are compatible with various wafer resistivities. As shown in Fig. 4, the ZEBRA cell concept demonstrates constant high efficiencies for wafer resistivities between 3 and 14Ωcm. In the case of the BiSoN cell concept, an increase in wafer resistivity leads to an increase in I_{sc}, while there is a slight decrease in fill factor (*FF*). Consequently, when integrating the BiSoN cells into the module according to an I_{mpp} sorting protocol, wafers with 2–10Ωcm resistivities can be used without any significant variation in cell (and module) efficiency. The cited resistivity ranges result in a high wafer yield, even for Cz-Si crystals grown by standard batch-type pulling.

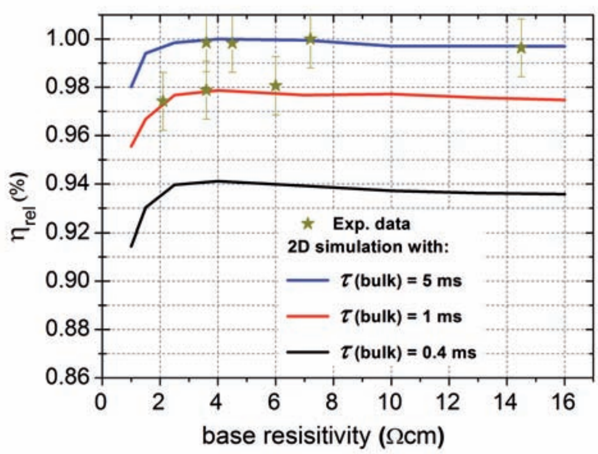


Figure 4. Experimental results and a 2D simulation of the relative efficiency variation of the ZEBRA cells as a function of base resistivity [4].

As regards the electrical quality, n-type Si is known to be more tolerant to common metallic impurities than p-type Si [5]. In combination with the absence of the LID caused by B–O complexes, this results in a high and stable minority-carrier lifetime compared with p-type Si. For this reason, the cell concepts with the highest efficiency potential – namely IBC and HIT – yield the best performance on n-type wafers.

Silver paste

The second most important item of the cell production cost is the metallization. The cost of current screen-printing technology is dominated by the cost of silver and the silver content of the paste used, and, of course, by the quantity of metal paste required for a particular cell concept.

Switching from the standard p-type Al-BSF (back-surface field) cell concept to advanced cell concepts, such as BiSoN or ZEBRA, basically means eliminating (cheap) Al paste and introducing (more expensive) Ag/Al paste for contacting the p^+-doped regions. Depending on the cell concept, it can be beneficial to combine a paste that is optimized for contact resistance with another paste that features a high lateral conductivity. If the contact geometry is optimized and state-of-the-art screen-printing technology is used, the metallization of advanced cell concepts can be implemented without increasing the production cost in US$/Wp at the module level, as demonstrated for BiSoN and ZEBRA cell concepts in the section 'Cost of ownership'.

Processes

As already mentioned, the applied processes are identical to those in standard p-type Si solar cell fabrication subject to a certain amount of tuning, along with some additional ones, such as advanced cleaning, BBr_3 tube diffusion, open rear-side Ag screen printing and (in the case of ZEBRA devices) laser ablation of dielectrics.

Etching, texturization and cleaning processes

The etching and texturization processes are very similar to those used for p-type processing. However, the fact that SiN_x is not etchable in NaOH allows the application of single-sided etching processes, for example to remove a diffused region from one side.

In order to obtain efficiencies above 20%, the surface pre-cleaning has to be better than that in standard processing. In addition, B diffusion takes place at higher temperatures, so metal contaminants must be removed from the surface more effectively. Such cleaning processes developed at ISC Konstanz are reviewed in Buchholz & Wefringhaus [6].

Diffusion and implantation

Since standard thermal diffusion processes (e.g. with $POCl_3$ and BBr_3 as dopant sources) using open tube furnaces are still adequate for achieving 21–22% efficiencies on a cell concept such as the ZEBRA IBC cell, these processes will continue to dominate, at least in the near future, because of their maturity, their cost effectiveness and, of course, the fact that the related production equipment is already present in existing cell-manufacturing facilities. However, since in the medium term the various roadmaps envisage efficiency targets of 23% in industrial production, it is expected that ion implantation will become more and more important. In fact, the values of the emitter saturation current J_{oe} required in order to achieve a cell efficiency of 23% are at a level that can be obtained, when using industrial processes, only with ion implantation. Important issues – apart from the equipment cost being still too high – are the optimization of the required annealing step, the tailoring of the doping profiles and the development of industrially viable masking processes. The EU-funded HERCULES project [7] aims to develop an IBC cell concept, and the related ion-implantation process, with a target cell efficiency of 24%.

Screen printing

Even though many innovative and promising metallization technologies have emerged in the last few years, the PV industry is still confident that screen printing of Ag-containing pastes will continue to play an important role, even when a timescale of 5 to 10 years is considered [8]. This is most likely due to the significant progress that has been made in screen-printing technology in the field of fine-line printing: 40-micron finger widths are now industrially feasible using double screen printing of Ag pastes [9], leading to higher efficiencies (as a result of reduced shadowing losses) and lower costs (because of reduced Ag consumption).

When considering cell concepts with a potential for high open-circuit voltages V_{oc} (e.g. BiSoN and ZEBRA), the use of currently commercially available screen-printing pastes represents a limiting factor for the effective V_{oc} that can be achieved in the final solar cell. This can be explained by the fact that during the firing process, metal penetrates the emitter and the space charge region, creating recombination centres and consequently increasing the J_{oe} [10]. For a bifacial n-type cell such as BiSoN, this means that the V_{oc}, for example, of the final cell is 650mV compared with the implied V_{oc} (before metallization) of 680mV or higher. As shown in Fig. 5, this loss in V_{oc} can be influenced by varying the emitter profile as well as by varying the total metal fraction. Another possibility for reducing the detrimental effect of screen-printing metallization is the modification of the paste composition. This approach has been adopted by Samsung, resulting in an IBC cell with screen-printed contacts featuring a V_{oc} of 670mV [11].

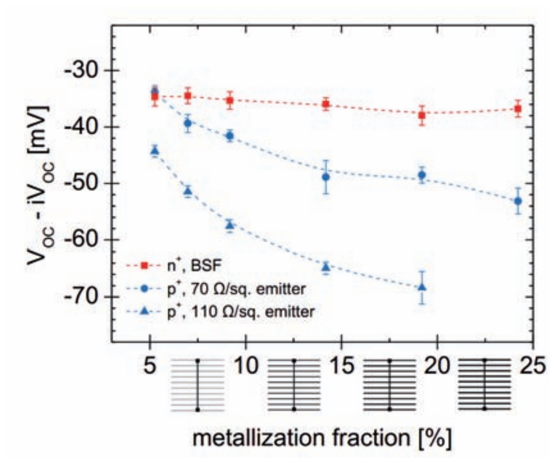


Figure 5. Net loss in cell V_{oc}, with respect to the implied V_{oc} value measured before metallization, as a function of screen-printed metal fraction on either a p^+ emitter or an n^+ BSF bifacial BiSoN cell.

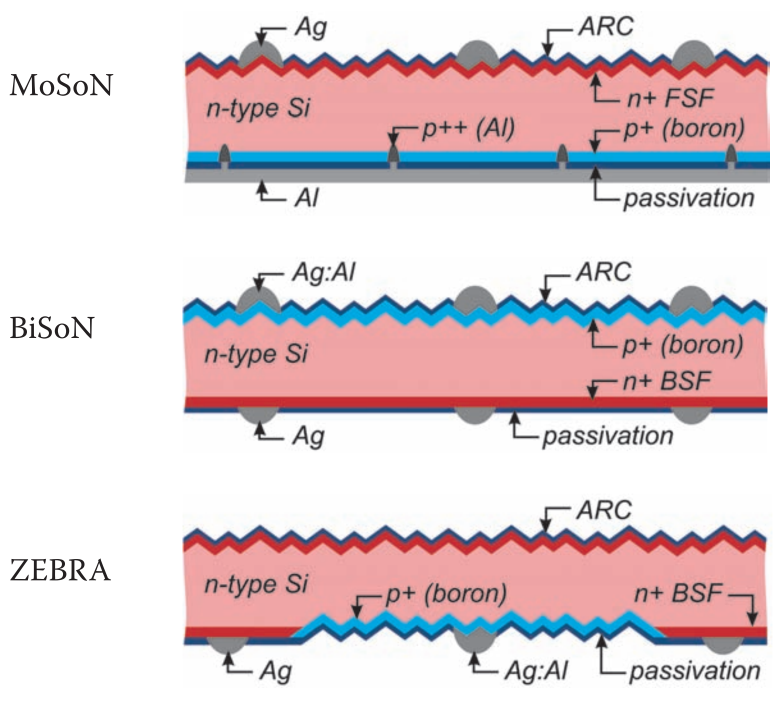


Figure 6. Detailed device cross sections of n-type concepts MoSoN, BiSoN and ZEBRA.

Ablation of dielectrics

When using dielectrics as masking layers, advanced cell concepts such as MoSoN and ZEBRA also require some process steps for the ablation of these layers. This ablation can be done either by the application of etching pastes or by using suitable laser systems. While the lasers are expected to offer an advantage in terms of running costs, the etching paste will be cheaper when taking into account the initial investment for equipment.

Device structures

As already described, with the availability of upgrades on the market for p-type devices the production of these can be switched to n-type concepts. The simplest device is MoSoN and the most complex one is ZEBRA, as shown in Fig. 6.

A p-type PERC structure can easily be transformed into a B rear-emitter PERT concept, called MoSoN, with only the implementation of a B diffusion on the rear. The other processing steps remain unchanged; however, they have to be slightly adapted to the n-type

device. With the implementation of MoSoN, a manufacturer has the easiest way of switching to n-type solar cells and benefits from higher and stable efficiencies because of the n-type substrate.

To reap greater benefits from the n-type substrate, both sides of the device have to be passivated by a dielectric, which results in the BiSoN device. The B emitter is then at the front, and the passivation layer is chosen to be a PECVD SiO_2/SiN_x layer because of its simplicity and stability. An AgAl paste is screen printed on the front; on the rear side, the device has a flat surface diffused in a $POCl_3$ tube furnace, passivated by PECVD SiN_x and metalized by screen-printed Ag paste.

One more step further along the roadmap results in the ZEBRA solar cell. The processing steps are similar to those for BiSoN, with the exception that the P and B regions have to be implemented alternately on the rear side. This can be done by using a diffusion barrier which is structured by a fast laser, as ~70% of the barrier has to be ablated. The passivations and metallizations are identical to those for the BiSoN device. To implement the busbars on the rear side there are several options, but the easiest one is to use an isolation paste which isolates every second finger underneath the busbar.

MoSon, BiSoN and ZEBRA – three industrially feasible devices which are diffused, passivated and screen printed on both sides – have the potential to achieve stable efficiencies well above 20%, with the ZEBRA device attaining 23%.

> "MoSon, BiSoN and ZEBRA have the potential to achieve stable efficiencies well above 20%, with the ZEBRA device attaining 23%."

Standard and advanced module concepts

Interconnection

The types of technology that can be used for the interconnection of cells within the module do not depend on whether the cells are p- or n-type, but only on the cell architecture. Accordingly, the various solar cell concepts discussed above can be divided into two main groups: two-side-contacted cells (BiSoN, MoSoN and PELICAN) and back-contact cells (ZEBRA). The two-side-contacted cells can be interconnected by the traditional soldering of ribbons using the same standard equipment as for today's mainstream p-type solar cells (Al-BSF and PERC). There are, however, several new and advanced interconnection concepts available, such as the gluing of standard ribbons using electrical conductive adhesives (ECAs) [12], multiwire technologies (e.g. Meyer Burger SmartWire [13] – Fig. 7), or the NICE module concept by Apollon [14] (which encloses the cells between two glass sheets under an inert atmosphere without any encapsulant, while the ribbons are connected to the cells by mechanical pressure alone). For those types of cell with an open rear-side metallization, all these interconnection technologies allow the fabrication of bifacial modules when using a transparent backsheet or glass on the rear side.

The back-contact cells (ZEBRA) can be interconnected by the soldering or gluing of ribbons: both of these options allow the fabrication of bifacial IBC modules. This can be done on an industrial scale by using dedicated tabber–stringers that are currently on offer or under development by various equipment manufacturers. Another option is the use of conductive backsheets, and a dedicated module manufacturing line has already been implemented on an industrial scale for the fabrication of MWT modules (e.g. Verschoor & Baake [15]). In this case the electrical interconnections are integrated within the backsheet and covered by an insulating layer that has openings corresponding to the respective contact points on the cells (Fig. 8). An ECA is then used to electrically connect the cells to the conductive backsheet. This technology features very low cell-to-module fill factor losses, while the manufacturing

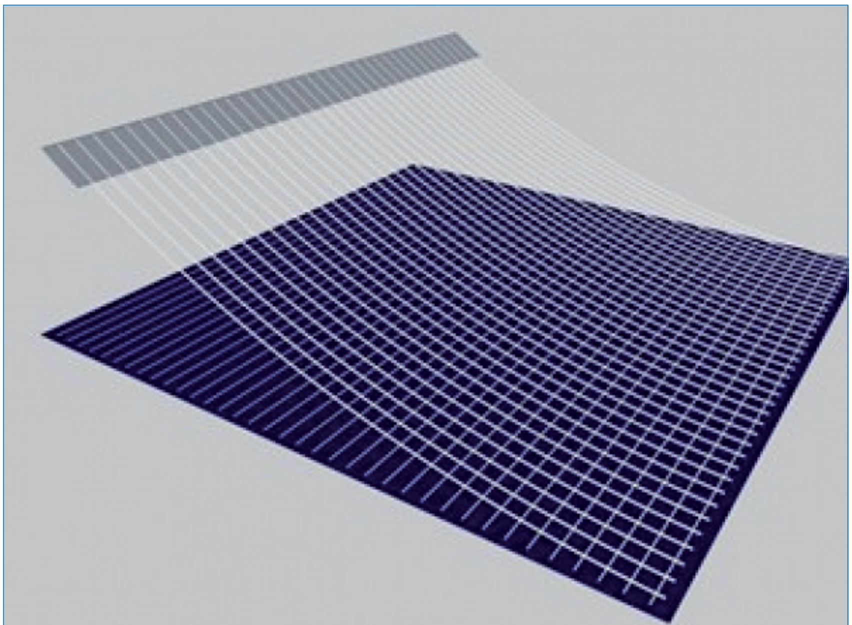


Figure 7. Schematic view of the SmartWire connection technology (SWCT) of Meyer Burger [13]: instead of interconnecting the cell busbars by means of two or three copper ribbons per cell, the busbar-less cells are interconnected by many thin wires.

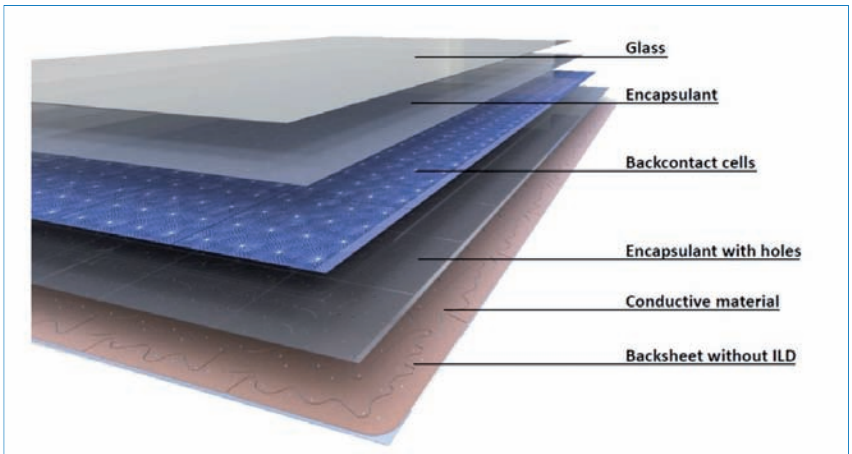


Figure 8. Cross section of an MWT module constructed with conductive backsheet technology [15].

lines are mostly suited to high throughput requirements (annual capacity over 150MW/year).

Encapsulation

Regarding the encapsulants, these must feature a high overall light transparency in order to transfer the maximum cell power to the module, i.e. achieve a minimum cell-to-module Pmpp loss. Because of the good spectral response in the UV range of the high-efficiency cells discussed in this paper, a high light transmission in the range 300–400nm is particularly important. As well as certain EVA encapsulants, alternative materials such as polyolefin-based sheets [16] and liquid silicone have proved to be satisfactory encapsulants with a high transmission in the UV range [17].

The light impinging on the area between the cells, as well as the light that crosses the entire solar cells without being absorbed, contributes to the optical cell-to-module losses. While the first component is also present in standard solar cells with a fully metalized rear side, the latter can cause significantly higher losses in bifacial cells. Consequently, when bifacial cells (BiSoN and ZEBRA) are integrated in monofacial modules, the use of highly reflective backsheets in combination with an optimized spacing of the cells helps to reduce the cell-to-module Pmpp losses: more light is reflected internally by the backsheet and therefore has a second chance of being absorbed by the solar cells.

Module lifetime

When carefully selecting the module bill of materials, today's industrial standards (80% residual module power after 25 years) can also be met using standard materials in the case of the advanced cell concepts discussed in this paper. Apart from keeping production costs as low as possible in order to reduce the module COO (US$/Wp), even for high-efficiency solar cells (see section 'Cost of ownership'), an increased module lifetime is another important factor that further reduces the levelized cost of energy (LCOE) for PV-generated electricity. In fact, using glass sheets instead of polymeric materials on the rear side of the modules, in combination with long-lasting encapsulant materials (e.g. certain silicone materials or no encapsulant at all, as in the case of the NICE concept), promises to deliver module lifetimes approaching 40 years or more.

Cost of ownership

At ISC Konstanz a comprehensive COO model for cells and modules has been created: this includes updated data regarding the cost and consumption of consumables as well as information about the CAPEX requirements for setting up the manufacturing lines for the various technologies. Among the various cost factors that have to be specifically adapted to the geographic location of the manufacturing site, the most prominent relate to energy (electricity, heating and cooling) and labour.

Another factor that can have a significant impact on the COO – in particular for the cell component – is the depreciation of equipment and buildings. Considering as a benchmark the standard technologies already present on the market, there is a vast array of possible CAPEXs subject to depreciation, ranging from an already existing amortized plant with standard technology (zero depreciation), to a completely new manufacturing line built from brand-new equipment (including the additional equipment for the advanced cell concepts, potentially requiring new equipment for the module line in the case of back-contact technology).

In order to correctly take into account the increased efforts in equipment spending for the advanced cell concepts, and in view of the fact that the concepts discussed herein can all be implemented as upgrades of existing standard p-type lines, the standard line (including factory building) has been considered amortized (no depreciation),

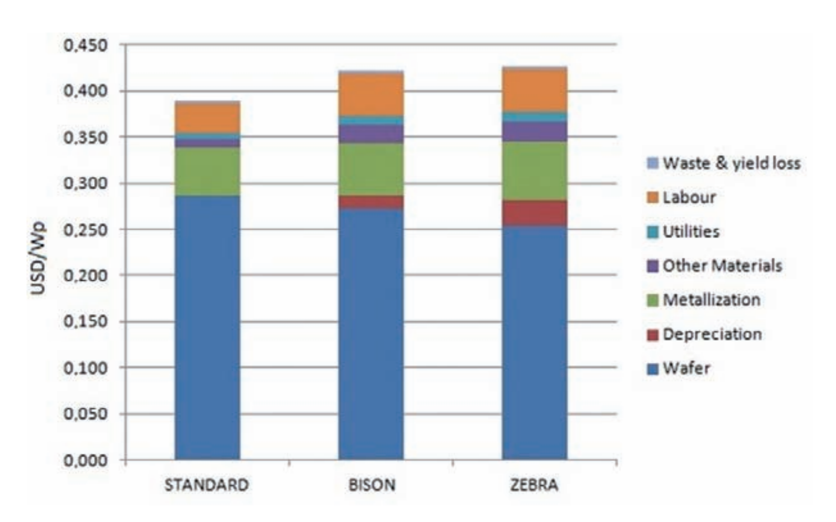


Figure 9. US$/Wp processing costs at a Chinese factory for p-type standard (Al-BSF) monocrystalline silicon cells compared with n-type BiSoN (bifacial, two-side-contacted) and n-type ZEBRA (bifacial back-contact cell) technologies. (Costs of US$1.3/wafer for 6″ p-type Cz-Si wafers and US$1.4/wafer for n-type wafers are assumed.)

while for the BiSoN and ZEBRA cells only the additional equipment and corresponding factory floor space has been taken into account. Under these assumptions, the COO calculations for a cell factory located in China (Chinese labour and energy cost) were performed at ISC Konstanz: the results are presented in Fig. 9.

> "For the move from BiSoN to ZEBRA, the cost of further process steps is offset by the higher cell efficiency."

The use of mature industrial process steps for the implementation of a high-efficiency cell concept minimizes the technological risk but requires an additional cost for equipment, labour, consumables and energy, which means an increased production cost per cell. As shown in Fig. 9, this additional cost leads to a higher US$/Wp when changing from standard to BiSoN, whereas for the move from BiSoN to ZEBRA, the cost of further process steps is offset by the higher cell efficiency. When this is examined at the module level (Table 2), the picture is quite different: because the module production cost (excluding cell cost) is more or less fixed independently of cell efficiency, the production cost for the high-power modules made from the advanced cells is only slightly (3–4%) higher than the cost for the standard cell modules.

As illustrated in Fig. 10, this affords the possibility of selling modules with a high efficiency (over 300W for a 60-cell module) at a price (US$/Wp) that is similar to the current market price of standard p-type monocrystalline modules (around 265W), thus offering very interesting market opportunities to cell and module manufacturers. From the point of view of the end customer, the moderate cost of high-efficiency modules contributes to a reduction in the cost of the installed PV system, and consequently to a decrease in the LCOE. It has to be mentioned that, in the COO calculations presented above, the fact that the BiSoN and ZEBRA cells are bifacial has not been taken into account. The benefits at the system level that can be realized from the use of high-efficiency bifacial modules will be discussed in the next section.

Future systems

BOS and LCOE

The overall objective of every R&D endeavour in the field of PV and related industrial projects for implementing new technologies is the continuous reduction of the cost of electricity generated by PV. The LCOE is defined as the total life cycle cost of a PV system (modules, BOS, maintenance, financing cost, etc.) divided by the total amount of kWh produced during the whole lifetime of the PV system. In recent years the reduction in the cost of an installed system has stemmed mainly from a significant drop in the price of modules and only partially from a cost reduction in the elements contributing to the BOS (inverters, installation cost, etc.). Although the rate of decrease in module cost has been markedly high for standard module technology, any future decreases are expected to be much slower. Consequently, decreasing the area-related BOS cost by increasing the module efficiency, while limiting the increase in module COO (US$/Wp), will become the most important option for further reducing the system cost (and consequently the LCOE) in the near future, as was shown to be the case for the BiSoN and ZEBRA technologies in the section 'Cost of ownership'.

> "The most significant increase in energy yield can be obtained by the use of bifacial modules."

Looking beyond the system cost, the increase in energy yield in kWh/kWp of a PV system under actual operating conditions is another approach to reducing the LCOE. The most significant increase in energy yield can be obtained by the use of bifacial modules: for example, the BiSoN and ZEBRA cells are bifacial and can thus be integrated in bifacial modules using transparent backsheets or glass on the rear side. When installed in a suitable configuration (high albedo from the ground, and optimized spacing between modules and/or cells), bifacial modules can yield a yearly energy production that is more than 20% higher than that of monofacial modules of the same size with the same front-side efficiency (see e.g. Sugibuchi et al. [18] or Eisenberg et al. [19]). Assuming that there is little or no increase in system cost in US$/kWp, a 20% increase in kWh results in a 17% reduction in LCOE, depending on the characteristics of the installation site. Another interesting application is the vertical installation of bifacial modules that are oriented in an east–west direction: in this configuration, bifacial modules feature an energy yield in kWh/kWp (kWp of front side) that can be 90% more than the energy yield from monofacial modules with an optimum tilt oriented towards the south [20]. Considering that during periods of high solar irradiation in certain regions with a high density of PV installations (Germany, southern Italy) the total electricity production exceeds total grid demand, the vertical installation of bifacial modules yields important benefits regarding the grid integration, as this set-up smoothens the peak of PV electricity production at noon and increases the electricity produced by PV in the morning and in the evening ('peak shaving').

Bifacial modules are also

particularly interesting for installations in desert regions. Fig. 11 shows an example of outdoor measurements performed at the ISC Konstanz testing and development site in El Gouna in Egypt (Fig. 12): these data show the solar irradiance measured over a period of 18 days on the front (red curve) and rear (blue curve) sides of a bifacial module installed above the sandy ground of the Egyptian desert. It can be seen that under these clear-sky conditions, peak irradiances of over 200W/m^2 (or more than 22% of the front-side irradiance) are obtained regularly.

Apart from the high albedo – which is beneficial for bifacial modules – desert regions feature a number of climatic characteristics that require a special design of the modules in order to guarantee a constantly high energy yield and a long module lifetime for PV systems installed in such harsh conditions. The high ambient temperatures demand that special attention be given to the temperature management of the module so that the operating temperatures are maintained below a certain limit. Furthermore, the strong UV irradiation is very punishing with regard to encapsulant lifetime. A particular issue is soiling by sand, which can greatly reduce the amount of light reaching the solar cells: under unfavourable conditions, the energy yield can be reduced by 35% or more (e.g. Ibrahim et al. [21]).

	Standard	BiSoN	ZEBRA
Cell efficiency	19.0%	20.0%	21.5%
Cell COO (US$/Wp)	0.39	0.42	0.43
Pmpp cell (Wp)	4.55	4.78	5.14
Cell to module (US$)	76	76	83
Pmpp module (Wp)	270.0	284.2	305.5
Module COO (US$/Wp)	**0.67**	**0.69**	**0.70**
Compared with standard		+3.0%	+4.4%

Table 2. COO calculation results for standard p-type monocrystalline silicon cell and module production compared with n-type BiSoN and ZEBRA technologies (monofacial modules).

Because of their high solar irradiation and the fact that these large areas of land cannot be exploited in other ways, the deserts in various regions of the world (e.g. MENA, South America, China) are increasingly attracting the attention of investors and the PV industry. For this reason, ISC Konstanz – in cooperation with institutes and companies in countries such as Chile and Egypt among others – is dedicating significant R&D resources to developing technical solutions for the design of modules that are high performing and long lasting when operating in the above-mentioned deserts.

Summary and outlook

As highlighted in this paper, solar cell structures are becoming more complex, resulting in higher efficiency devices, but not, however, an increase in cost per Wp. Because the installation surface area for such devices with equivalent power generation is decreased, the BOS cost is automatically reduced; if bifaciality is also considered, the costs for such a system can be decreased even further. Calculations reveal that in this case, if installing a large PV system in, for example, the Atacama Desert (Chile), the cost of PV-generated electricity can be reduced to US¢2–3/kWh [22].

It is therefore extremely important for future solar cell concepts not to compromise cell efficiency. ISC Konstanz has a roadmap that targets an efficiency of 24% by 2017 with the use of low-cost processes which can be incorporated into existing production lines (Fig. 13).

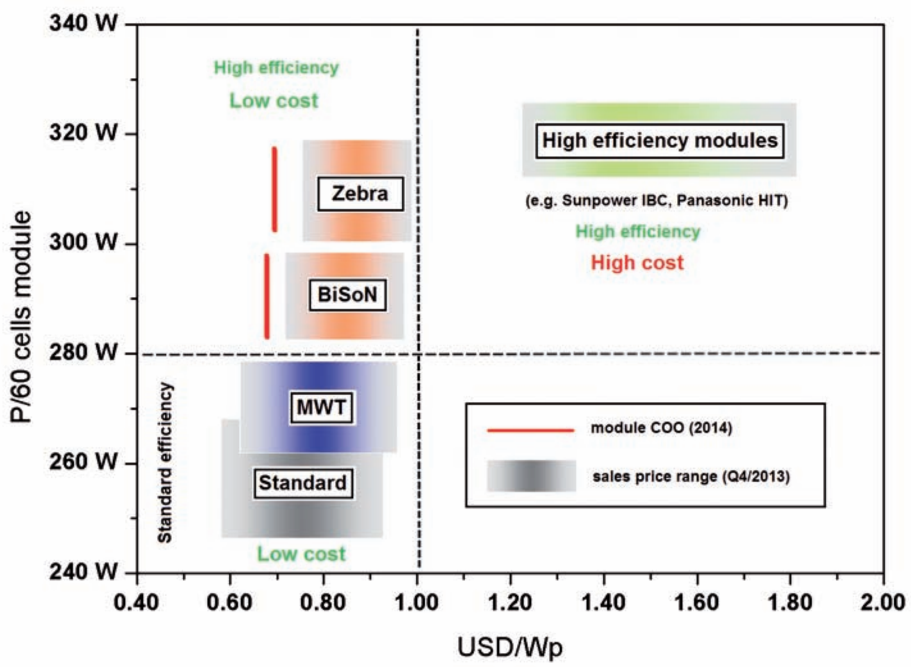


Figure 10. Efficiency (expressed as the Pmpp of a 60-cell module, assuming 6″ cells), COO and possible sales price ranges (US$/Wp) for BiSoN and ZEBRA modules compared with various PV technologies currently available on the market.

> "To compete with large Asian manufacturing lines in PV production, it is not only size but also advanced technology that matters in achieving higher module powers at similar costs per Wp."

To achieve this roadmap goal, ISC Konstanz is participating in several EU and national projects, such as ModerN-Type, MetalTopp, HERCULES and 10ct, which all have in common the assembling of the pieces of the puzzle to create a 24%-efficient ZEBRA solar cell. In ModerN-Type (Eurostar E!7232), together with Eurotron, a rear-contact module concept is being developed based on conductive backsheet technology, whereas in MetalTopp (BMU FKZ 0325569B), screen-printing pastes are being developed for contacting p^+ surfaces with the aim of reducing the metallization-induced V_{oc} losses. In the case of 10ct (BMU FKZ 0325679B) and HERCULES (EU-GAN 608498), IBC technologies based on diffusion and ion implantation, respectively, are the focus. The plan to build a large 1–1.5GW factory in Europe, shared between France, Germany and Switzerland (similar to the Airbus consortium), was announced by French President François Hollande; this is considered to be predestined for implementing advanced low-cost technologies under development within the HERCULES project [7,23].

As demonstrated above, in order to be able to compete with large Asian manufacturing lines in PV production, it is not only size but also advanced technology that matters in achieving higher module powers at similar costs per Wp.

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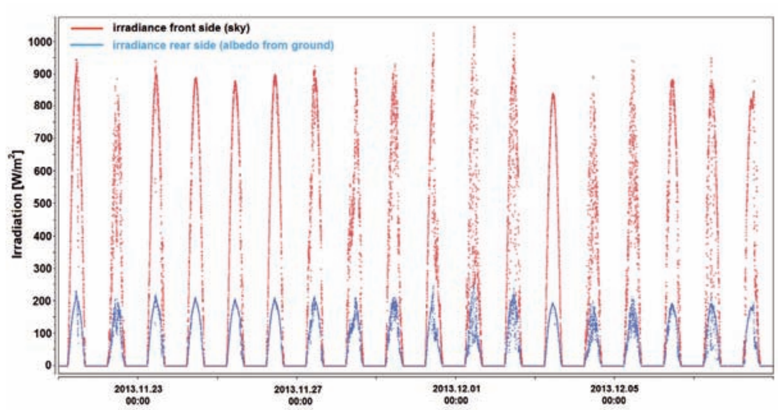

Figure 11. Outdoor measurements taken at the ISC Konstanz module test site: front-side (red) and rear-side (blue) irradiances measured on a bifacial module (20-degree fixed tilt) installed in the desert near El Gouna in Egypt.

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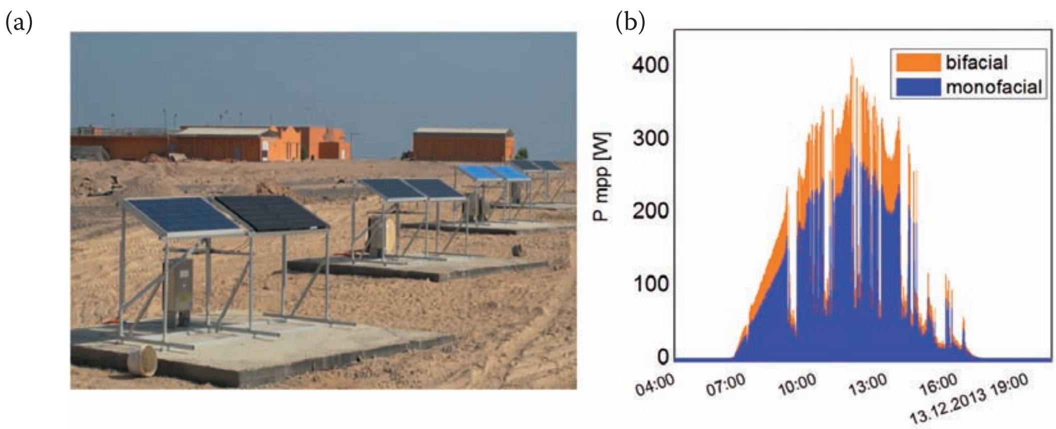

Figure 12. (a) ISC Konstanz module test site in El Gouna (Egypt); (b) Pmpp measurement of a bifacial module, reaching 400W around noon.

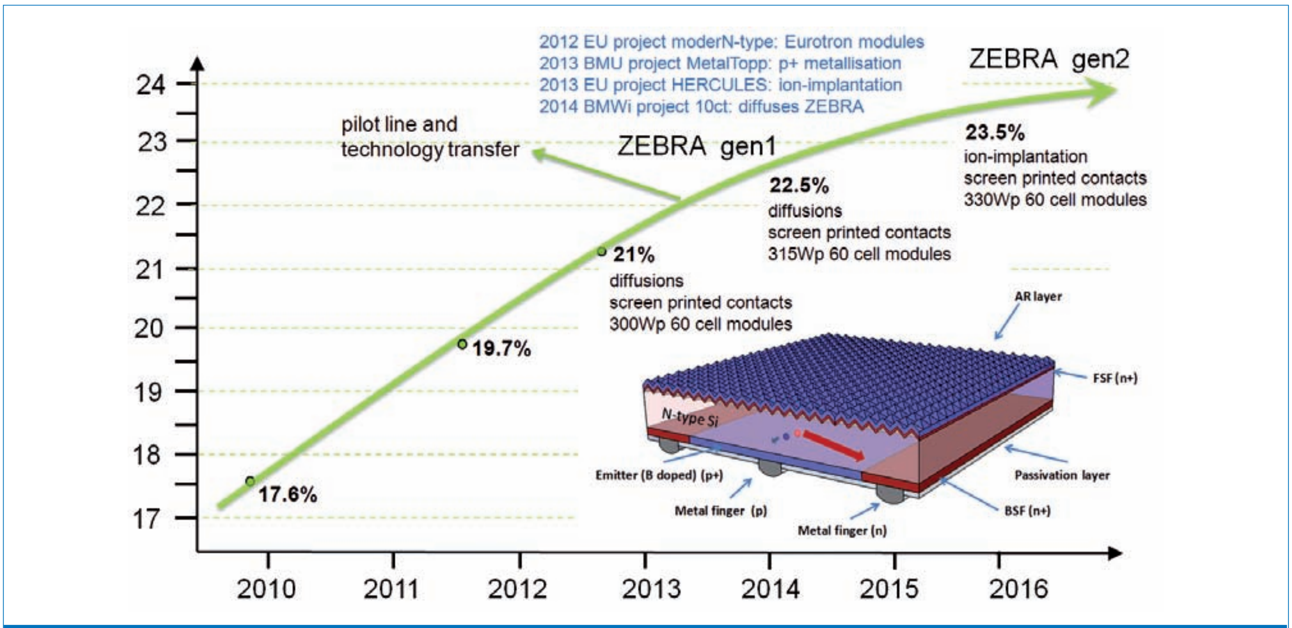

Figure 13. Efficiency roadmap for the ZEBRA solar cell.

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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.

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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 of Science from Portland State University (Oregon, USA) in 1995, and then obtained his Diploma in physics at 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.

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Cell metallization by screen printing: Cost, limits and alternatives

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ABSTRACT

Although considerable progress has been made in reducing the amount of Ag required per wafer in the classic screen-printing metallization of Si solar cells, the total cost of ownership of the metallization process today accounts for more than 50% of the total cell-process-related cost. There has been pressure on cell and module manufacturers to further reduce this cost, by either improving the metallization process or applying alternative contacting technologies. In this paper, the classic screen printing of standard Si-based solar cells, which has been the main metallization technique for many years, is described in detail. The required paste volume for providing the contacts in a state-of-the-art cell production process is calculated on the basis of the contact dimensions (fingers and busbars on the front, Al layer and Al/Ag pads on the back). Taking into account today's paste prices, equipment investment, screen cost, energy, maintenance, yield, material utilization and necessary labour, the total cost of ownership of the cell metallization is also determined. The main cost drivers are discussed in detail. The cost reduction is estimated when improved printing processes – such as double, dual or stencil printing – are employed. Other promising alternative front-contact metallization technologies are listed and their potential is briefly discussed. To evaluate the competitiveness of these technologies, the limit of today's screen-printing method and its further cost-reduction potential are estimated on the basis of the physical properties of cells and printing pastes.

Introduction

The screen printing of Si solar cell contacts with silver- and aluminium-based pastes was first reported in 1975 [1]. Since then, screen printing has evolved to become the dominant contact metallization technique: more than 95% of today's wafer-based commercial Si solar cells feature screen-printed H-pattern Ag contacts on the front side and a full-area Al contact with Al/Ag solder pads on the rear. Commercial screen-printing equipment today is fully automated, and the process is simple, reliable and robust while providing high throughput. Many different suppliers exist for manufacturing tools, printing screens and pastes.

> "The total cost of ownership of the metallization process today still accounts for around 50% of the total cell-process-related cost."

Significant progress has been made in efforts to reduce the amount of Ag required per wafer, but the total cost of ownership of the metallization process today still accounts for around 50% of the total cell-process-related cost. Cell and module manufacturers are consequently investigating ways of further reducing this cost, for example by improving the metallization process or employing alternative contacting technologies.

In this paper, the total cost of ownership of the classic screen-printing metallization of standard Si-based solar cells is calculated taking into account all relevant data in a cell production line. Furthermore, estimates are given for the cost reduction in the case of improved printing processes, as well as for the cost limit determined by the physical properties of the cell device and pastes. Several promising front-contact metallization technologies are listed and discussed, along with potential hurdles for their industrial introduction.

Front side

On the front side of the cell, the metal grid consists of silver paste. The main structure consists of the fingers (which collect the current from the emitter of the solar cell) and the busbars (which collect the current from the fingers and provide the solder contact area to the ribbons when a string is formed). The standard structure of the front contacts nowadays is the three-busbar design: the fingers usually have a spacing of 2–3mm and a width of 60–100µm, the busbars are 1.5–2mm wide, and the height of the structure is approximately 25µm. Many different and partially conflicting requirements of the front-side grid and the respective Ag-based paste have to be fulfilled:

- Low shadowing area.
- Minimum contribution to the series resistance of the cell: low contact resistance to the emitter and low finger bulk resistivity.
- Grid fingers with a high aspect ratio to allow both a low fraction of shaded cell area and a low series-resistance contribution.
- Low silver usage to save material cost.
- Sufficient etching of the paste through the SiN_x anti-reflection layer, to form good electrical contacts.
- Adequate adhesion to the Si wafer.
- Good solderability for string formation.
- High reliability/durability when the cells are deployed for field operation.
- High print quality, with a minimum number of finger interruptions and a homogeneous structure, even for fine-line printing.
- Paste with a long shelf and pot life, constant and stable rheology, and no critical agglomerates or segregations.

Being one of the best conductors, silver in the form of powder is the main paste component, with 70–85 wt%. At low temperatures silver does not react with SiN_x and Si: therefore, 1–10 wt% lead-borosilicate glass powder is typically added to the paste – its main task is to etch through the SiN_x layer and to establish an electrical and mechanical contact to the silicon. The binder and solvents are used to tune and guarantee good printing properties and a high shelf life.

The efficiency losses related to front-side metallization are due to:

- Recombination of photo-generated charge carriers (not discussed here).
- Shadowing of 5–10% active cell area (resulting mainly in short-circuit current – I_{sc} – loss).
- Series resistivity contribution of the finger contact resistance and the finger bulk resistivity (resulting in fill factor – *FF* – loss).

To keep the active area loss at a low level, the finger width has to be reduced; however, in order to avoid the resulting high series resistance losses, the finger height – i.e. the aspect ratio of the fingers – has to be increased.

Rear side

In comparison to the front side, the requirements for the rear-side metal contact are relaxed, since the main material – aluminium – is less expensive, and the dimensions of the printed structures are not in the critical range with respect to the screen geometry. Thick-film pastes for the metallization of the boron-doped base are applied to the full cell area: therefore, neither a low specific contact resistance nor a high aspect ratio is required. For this type of paste the challenge is to reduce recombination on the rear side of the cell. In common industry-standard cells, a heavily doped p region – or back-surface field (BSF) – is introduced below the metal contact. This is realized by using aluminium as the active metal in the rear paste, because it acts as a p type dopant in silicon.

The rheology of an Al paste for full-area metallization is different from that of a front-side paste. The binder and solvent have to ensure that the substrates do not stick to the screen after a printing step. The paste must be deposited with a homogeneous thickness over the whole area. The viscosity of the paste compared with front-side pastes is therefore often lower. Glass is not necessarily added to a rear-side paste.

An important consideration for Al pastes is the coefficient of thermal expansion (CTE) during drying and firing. The CTE is optimized for minimum mechanical stress, and therefore lowest possible wafer bowing, which reduces cell breakage rates in manufacturing.

As aluminium in not solderable, the contact area for the interconnection with ribbons on the rear side is provided by Ag/Al pads, and the rear-side Ag paste for these pads has a lower Ag content than the front-side Ag paste.

No. of fingers	78	No. of busbars	3
Finger width	80µm	Busbar width	1.5mm
Finger height	25µm	Busbar height	25µm
Finger length	14.95cm	Busbar length	154mm
Finger area	9.33cm^2	Busbar area	6.93cm^2
Finger volume	0.0233cm^3	Busbar volume	0.0173cm^3
Finger area fraction	3.83%	Busbar area fraction	2.85%
Total area covered	16.26cm^3	Total paste volume	0.0407cm^3
Cell area	243.36cm^2	Paste density	3.25g/cm^3
Shaded area	6.68%	Ag paste required	0.132g

Table 1. Front-side properties.

Screen printing and firing process

For the printing process, a fine-mesh print screen, mounted within a frame, is placed over the wafer; the screen blocks off certain areas and leaves other areas open, where the printing paste can penetrate. After a predefined amount of paste is dispensed onto the screen, a squeegee distributes the paste over the screen, to fill the screen openings: as the squeegee moves across the screen, it presses the paste through the screen openings and onto the wafer surface. In order to obtain a high print quality, this process must be tightly controlled for temperature, squeegee pressure, angle, speed, screen and squeegee materials and properties, paste specifications, etc. [2].

After each printing step, the wafer proceeds to a drying furnace to solidify the paste at a temperature of 200–300°C for typically 20–120 seconds, depending on the specific pastes being used. The wafer is then transferred to another printer for printing additional lines on either the front or rear side of the wafer. When all printing steps have been completed, the wafer is 'co-fired' in a high-temperature furnace, where the final formation of the contacts – especially the etching of the SiN_x and the formation of the BSF – takes place at temperatures of around 850°C. Since both the back- and front-side contacts form at the same time and same sequence in the process, this step is called 'co-firing'. Because the front-side requirements are more stringent, the firing process is optimized for the front-side metallization, and on that basis, the rear-side metallization is adjusted to suit these firing conditions.

No. of pads	18
Pad size	0.2025cm^2
Al laydown	5.50mg/cm^2
Al-coated area	239.715cm^2
Al paste required	1.318g
Ag/Al laydown	4.2mg/cm^2
Ag/Al pad area	3.645cm^2
Ag/Al paste required	0.0153g

Table 2. Rear-side properties.

The metallization – in particular the firing stage – is the most complex process step in the production of industrial solar cells: in none of the other steps do so many processes occur simultaneously.

> "The metallization is the most complex process step in the production of industrial solar cells."

Detailed grid dimensions and paste usage

In determining the amount of paste that is required for the formation of a state-of-the-art front- and rear-side metallization, the paste properties and dimensions shown in Tables 1 and 2 are assumed. With these assumptions of 80µm finger width, 25µm finger and busbar heights, and 1.5mm busbar width, the requirements per wafer are 132mg Ag paste for the front-side grid, 1318mg Al paste for the rear side, and 15.3mg Ag/Al paste for the rear-side solder pads. The shaded front-side area is about 6.7%.

It is assumed that 130mg of Ag paste per wafer is today's best-in-class result in high-volume industrial production by using off-the-shelf screen-printing equipment and high-quality screens and Ag pastes in a one-step printing process.

Because of cost-saving pressure, Ag usage has significantly decreased in recent years. Yet, in 2010 the Ag usage was around 300mg per wafer [3]. The reduction in silver consumption has been realized by the following improvements:

- Lower contact resistances, allowing narrower fingers without fill factor losses.
- Rheology adjustments to permit the printing of finer lines with better homogeneity and aspect ratio. Clogging of the fine meshes by paste agglomerates is reduced.
- Screen printers that have greater accuracy.
- Screens with finer meshes, so that finer finger lines without finger interruptions can be printed.

Total cost of ownership calculation

The basic assumptions for this calculation are as follows:

1. Screen printer and production numbers
Throughput is 3200 wafers/hour, corresponding to about 100MW/year, with 18% cell efficiency, consisting of three print heads, three drying ovens and one firing furnace. Necessary building space is around 200m^2. Specified wafer breakage rate is <0.15%. Number of production days per year is 360, with 24/7 four-shift operation. Equipment uptime is 90%, metallization line yield is 99.7% (0.15% breakage and 0.15% optical/electrical loss). Cells with 18% efficiency (4.2Wp) are used, and each scrapped cell in the metallization line is accounted for by a cost of €0.8.

2. Investment
Depreciation time for this calculation is five years. Investment for metallization line – including dryers, firing furnace and screen-washing station, but with no advanced quality-control systems or manufacturing execution system (MES) – is €2,500,000.

3. Labour cost
In a production configuration with multiple metallization lines and 24/7 four-shift operation, it is estimated that one engineer (€50,000/yr), four technicians (€35,000/yr) and eight operators (€20,000/yr) are necessary per metallization line of 3200 wafers/hour.

4. Energy cost
Average power consumption of 100kW is estimated for the operation of the line, including technical supply. Energy cost of €0.06/kWh is accounted.

5. Building and technical infrastructure cost
Around 200m^2 floor space per line is necessary. Building cost, including technical infrastructure, is accounted at €2500/m^2.

6. Maintenance cost
Estimate of 5% yearly of initial equipment investment is reckoned for maintenance of the metallization line, including technical infrastructure but excluding printing screens.

7. Printing paste required per wafer
According to the dimensions assumed in Tables 1 and 2, ~0.13g Ag paste for the front-side grid is calculated. For the rear side, ~1.3g Al paste and ~0.015g Ag/Al paste per wafer is needed. Paste laydown for the rear side is in accordance with the specification of leading paste suppliers. Material utilization of 98% is estimated.

8. Paste cost
The selling prices of Ag-containing pastes are usually coupled to the Ag world market prices. For this calculation, the price assumptions are €750/kg for the front Ag paste, €600/kg for the rear-side pad paste, and around €18/kg for the Al paste.

9. Printing-screen cost
Printing screens generally have a wide window of cost vs. quality (i.e. maximum number of good prints). Values of €100 per 10,000 print steps for front-side screens and €28 per 10,000 print steps for rear-side screens are assumed.

> "The total cost of ownership is dominated by the materials cost."

When all the above data is fed into the cost model, the results shown in Table 3 are obtained. The total cost of ownership is €ct4.69/Wp and is dominated by the materials cost, which together add up to €ct3.18/Wp, or around two-thirds of the total cost. The cost of the Ag front-side paste, at €ct2.38/Wp, contributes to over 50% of the total value (Fig. 1). Other main cost drivers are, at close to 10% each, production equipment investment (10.2%), labour cost (7.2%) and screen cost (8.0%). The other categories – maintenance, building investment, energy and scrap – collectively account for around 7% of the total cost.

	€ct/Wp	%
Scrap	0.06	1.2
Investment	0.48	10.2
Labour	0.34	7.2
Energy	0.05	1.1
Building	0.10	2.0
Maintenance	0.12	2.6
Ag paste	2.38	50.6
Ag/Al paste	0.23	5.0
Al paste	0.57	12.1
Screens	0.38	8.0
Total	4.69	100.0

Table 3. Total cost of ownership as calculated using PICON Solar's model.

When the total cost is divided between the front and rear sides, around two-thirds (€ct3.18/Wp) is attributable to the front contact and one-third (€ct1.51/Wp) to the rear contact (Fig. 2).

The Ag paste for the front side is the main cost driver and its price is very unstable. As already mentioned, the paste consists of 75–85% silver. Usually, manufacturers link the selling price of their pastes to the Ag cost on the world market at the time of ordering. The above metallization cost of around €ct4.7/Wp is calculated on the basis of a silver paste cost of roughly €750/kg. If it is assumed that 80% of the selling price of the paste is coupled to the Ag market price, and this assumption and the last five years' extreme Ag stock prices of $10 and $50 per troy oz [4] are transferred to PICON Solar's cost model, the cost of screen-printed cell metallization might be as low as €ct4/Wp or as high as €ct8/Wp.

The high sensitivity of paste cost to the Ag market price is a serious issue for cell and module manufacturers. PV has been one of the main drivers for the increase in Ag market volume during the last 10 years. In 2013 the PV-generated silver demand was around 100M ounces, which already corresponded to 15% of the world Ag market [5].

> "PV has been one of the main drivers for the increase in Ag market volume during the last 10 years."

It is not within the scope of this work to project future Ag prices, or future PV production and its influence on


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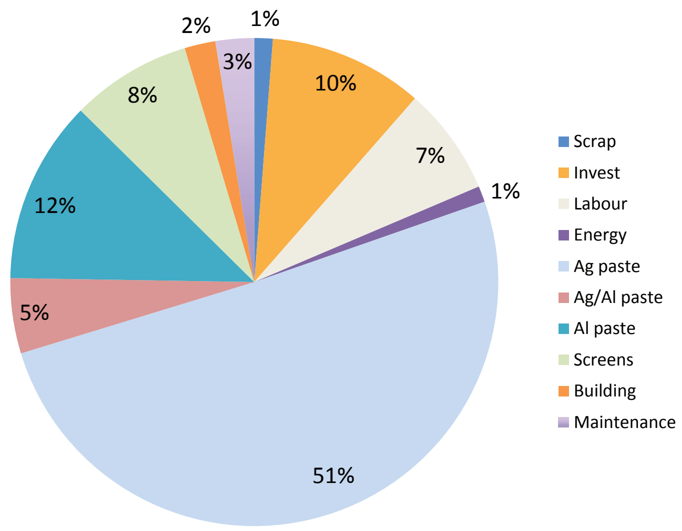

Figure 1. Metallization process cost structure.

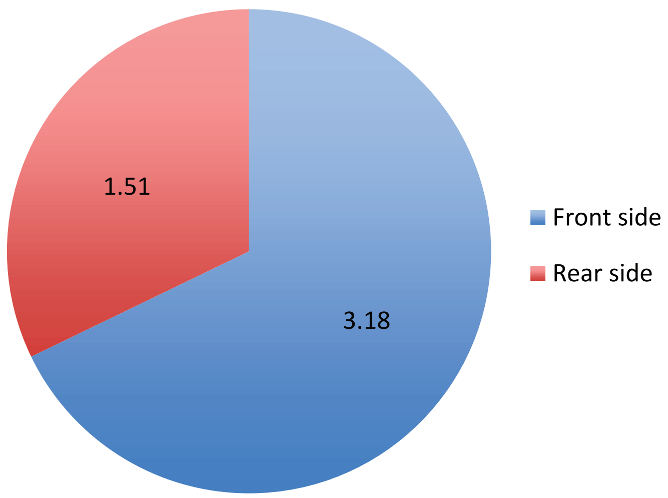

Figure 2. Costs related to front and rear contacts.

silver paste cost. However, it needs to be stated that this factor represents a major uncertainty in predicting the future cost of Ag-based screen printing, and that this fact is important if alternative metallization methods are considered.

Cost limits of screen-printing technology

Dual-printing and double-printing methods allow the aspect ratio of the finger lines to be increased and/or the printing of busbar and grid lines to be decoupled using different screens and pastes which are adapted to each purpose. Ideally:

- The grid lines are ≥20µm high and optimized for contact as well as bulk resistance.
- The busbars are ≤10µm high and are optimized for bulk conductivity. To avoid very powerful short circuits under the busbars, the paste should not etch the SiN_x, i.e. should not contain glass frit.

The two printing processes are defined as follows. *Double printing*, in theory, means to print two identical structures one on top of the other; this helps to achieve a better finger aspect ratio, because the lower height allows more accurate paste transfer, and drying after each printing step stabilizes the paste, keeping it from spreading. *Dual printing*, in theory, means to print the grid lines and the busbars separately; this allows two different structures of different heights and with different pastes to be printed.

In practice, however, double printing is often combined with dual printing, and this can be accomplished as follows. In the first step, the grid fingers of ~10µm in height are printed using a contact-optimized paste, and then dried. In the second step, the complete H pattern of ~10µm in height is printed exactly over the first print pattern, but with a paste optimized for bulk conductivity, and then dried again. The double/dual-printing approach offers a combination of features:

- An improved aspect ratio for the grid lines (i.e. less cell shadowing), with no increase in series resistance.
- A 50% saving of Ag paste for the busbars.
- The avoidance of shorts under the busbars by using a non-etching paste, thus improving cell performance.

As a result of the geometrical grid model, it is estimated that the cell efficiency can rise by 1–2% (relative), and that the Ag front-side paste usage can be reduced by around 35%. The drawbacks of this approach are that the alignment precision of the first and second print steps must be better than ±10µm, otherwise there will be finger interruptions or the fingers will be too wide. To achieve this alignment accuracy between the two printing steps, there are several requirements:

- The machine precision must be improved to enable the screen frame to be accurately positioned.
- Alignment marks on the cell together with an optical control system must be used for automated overlay positioning.
- A high matching accuracy of ±5µm and distortion-free screens (≤10µm over the lifetime) must be used to allow good overlay.

As additional investment for this process, another print head and drier are necessary, advanced process control for alignment and screen distortion monitoring needs to be implemented, and high-quality screens must be used. On the basis of the additional tool investment, the higher front-side screen cost and the increased engineering labour cost to maintain the more complex process, a payback period of around two years is calculated.

The principal cost limit of the Ag-paste-based H-pattern screen-printing technology will be discussed next. The current standard process is basically limited by two factors:

- The printing of fine lines with a high aspect ratio, while keeping the screen cost and equipment/process complexity low.

- The use of pastes having mechanical properties suitable for fine-line printing, low contact resistance for high-ohm emitters, and high finger conductivity.

On the assumption that these aspects will be further improved in the next few years, a theoretical calculation can be carried out to determine the minimum amount of silver paste needed for optimized Ag grids. Hannebauer et al. [6] calculated the optical and electrical loss contribution of the grid as a function of paste resistivity, finger width, and aspect ratio. On the basis of a realistic aspect ratio of 0.5 and state-of-the-art and future-optimized pastes (a quarter the contact resistance and around twice the finger conductivity compared with today's values), an optimum finger width in the range of 30–35µm is calculated. If, additionally, segmented busbars (1.5mm in width, 12µm in height) are assumed, and these values are fed into the geometrical model, the result for the standard three-busbar H-pattern geometry is a Ag paste usage of about 40mg for the front side.

With similar assumptions to those for double/dual printing (increased equipment investment, engineering resources, screen cost), the result is a total cost of ownership that is higher than the low silver consumption suggests.

An overview of the cost of ownership for the single-print and double/dual-print approaches and the future 40mg scenario, as a function of current, halved or doubled Ag paste prices, is given in Fig. 3.

The cost advantage of reduced Ag paste usage is not as pronounced as might be expected, because it will be partially counteracted by the higher screen cost and increased process and equipment complexity. However, in the case of rising Ag prices, the advantage is very clear.

> "The cost advantage of reduced Ag paste usage is not as pronounced as might be expected."

Potential alternatives

Other possible options are in principle the following lines of approach:

1. Retain the printing process:
   (a) use non-Ag-based pastes, or
   (b) stay with Ag and reduce requirements by employing an alternative cell interconnection.

2. Integrate an alternative metallization process:
   (a) stay with Ag and reduce consumption, or
   (b) keep Ag as a seed layer and use low-cost bulk conductor material, or
   (c) completely replace Ag by other materials.

A full discussion of all alternative processes, materials and methods is beyond the scope of this paper, but some general thoughts should be given on a few of the ones for which industrial application is imminent:

- The *multi-busbar approach* belongs to category 1(b) above. Theoretically, with a 15-wire geometry, reduced series-resistance loss and greater active area, the cell efficiency could be increased compared with a three-busbar setup [7]. An effective electrical grid finger path length of around 5mm means that the need for high aspect ratio grid fingers is greatly relaxed and 17µm-wide fingers would be sufficient. This would result in a theoretical silver paste requirement of less than 10mg per Wp [7]. While requirements of less than 70mg have already been published, a further significant reduction would demand techniques other than grid screen printing, such as ink jetting an Ag seed layer and adding a cheaper bulk conductor by plating. Concerns from the authors' point of view are the higher equipment investment in modified stringers and the increased string/module scrap in production as a result of the soldering and handling of fragile multiwire strings.

- The *smart wire approach*, again in category 1(b), also enables improved efficiencies by both lowering the series resistance and avoiding the shading of the active cell area by large busbar structures [8]. In this technique only the finger structures are screen printed on the cell. Copper wires covered with a low-temperature melting alloy, which are integrated in a transparent polymer film, form the contact to the rectangular grid fingers in the lamination process. Again, because of a low effective finger length, high aspect ratio grid fingers are not necessary, and the silver consumption can be greatly reduced. The authors' concern here is that when the low-temperature melting alloy covering the Cu wires is indium based, the cost-reduction potential of this method might be insufficient.

- The *copper plating approach*, which falls into category 2(b) or 2(c), could be implemented in many different ways. An Ag-based paste could still be used to form the contact to Si; as the bulk conductor, Cu

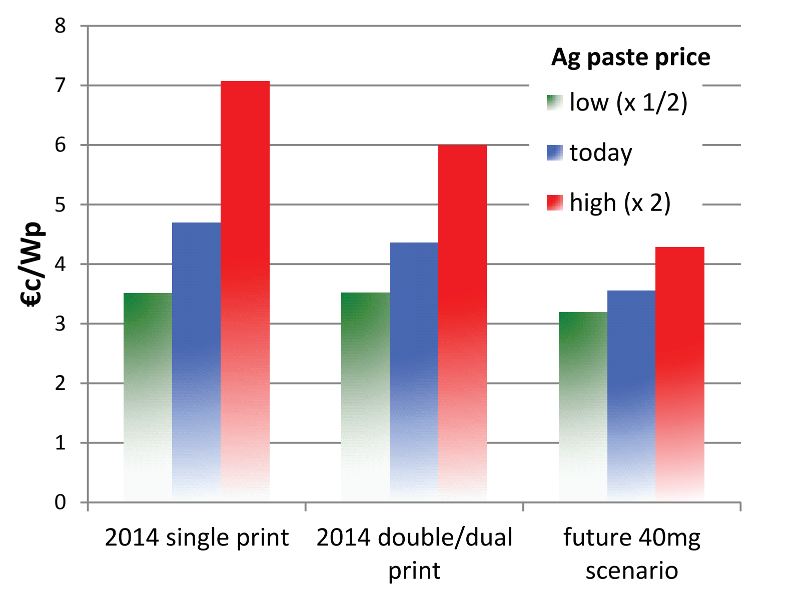

Figure 3. Metallization cost as a function of the type of process and the paste price.

could then be plated on top of the paste, followed by a Sn capping layer for soldering. An even more attractive option appears to be a Ni/Cu/Sn grid structure, with the metal material cost reduced by a factor of around 100. Challenges for this process are, in particular, controlling the formation both of the NiSi contact and of the anti-reflection layer opening (the latter by laser structuring or a chemical etching process). The authors' concerns are possible reliability issues due to Cu diffusion, especially in the case where no masking layer is applied during copper deposition. If a masking layer were applied, the process might become too complex and consequently expensive.

Conclusion and outlook

From a cost perspective it is clear that potential alternative metallization processes need to demonstrate a total cost of ownership today below €ct4.7/Wp, and a cost-reduction roadmap that targets a value significantly below this.

> "Achieving a sufficient cost-reduction potential for the front side is one of the major challenges."

For all alternatives that are relatively close to being industrially applied, the authors believe that achieving a sufficient cost-reduction potential for the front side is one of the major challenges. Besides this, reliability-related concerns as a result of introducing new methods, especially with respect to compatibility with various material combinations in a PV module, have to be eliminated. Performance stability in the face of accelerated testing under standard and certain non-standard IEC conditions must be ensured, which might be a huge hurdle for the introduction of a new technology into mass production. Additionally, for all alternative contacting and interconnection methods, it needs to be proved that sub 160–180µm wafers can be handled without a significant increase in production scrap.

Rising Ag market prices in the future, however, will intensify the pressure on cell and module manufacturers to pursue alternative methods. A detailed investigation of the cost and reliability of these methods will reveal which alternative process is the best option for the future.

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About the Authors

Dr. Steffen Schuler has 15 years' experience as a physicist in public R&D, product development and production optimization in the VLSI semiconductor industry and PV. Before joining PICON he was a team leader for product engineering at Infineon/Qimonda and a member of the management team of Global Solar Energy Deutschland as Head of Technology.

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Thin Film

News

Solar Frontier posts first annual profit thanks to Japanese market

Leading CIS thin-film PV module manufacturer, Solar Frontier, reported its first annual profit in 2013, fuelled by the boom in the Japanese market.

Showa Shell Sekiyu reported its Energy Solution Business, which contains Solar Frontier, reported net sales of JPY141.2 billion (US$1.38 billion), up 80.4% from the previous fiscal year, and an operating income of JPY17.5 billion (US$171.7 million), up JPY32.9 billion compared with the previous fiscal year.

Profitability for the first time for Solar Frontier was said to have been due to increased module shipments, operating at full capacity and manufacturing cost reductions of 20%.

Over 90% of total shipments in 2013 were targeted for the Japanese market with a focus on residential, commercial and utility-scale (mega solar) markets. Solar Frontier plans to increase its focus on the Japanese residential market in 2014, after launching lighter weight modules and a new roof mounting system to reduce installation times and balance of system costs. The company also plans to focus on the smaller industrial systems market in Japan on the expectation of feed-in tariff reductions as well as continue to strengthen its market share in the utility-scale sector. The company is therefore continuing to focus the majority of its sales on the Japanese market in 2014.

Source: Solar Frontier.

Japan's booming market has enabled Solar Frontier to post its first annual profit.

India's national solar programme

First Solar set to miss out in India PV auction

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

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

Overall 58 developers bid for 122 solar projects. The financial bids followed a technical qualification round. Developers competed in the reverse-bid auction in two parts. Half the 750MW available had a mandatory domestic content requirement (DCR), and the other 375MW was left open with no domestic requirement. The US filed a complaint to the World Trade Organisation earlier this month claiming that it should have equal access to the procurement round.

First Solar has previously dominated the thin-film market via a loophole in previous JNNSM bids, now closed, which did not include thin-film modules under DCR. The company has worked with the US Export-Import Bank on a number of projects in India.

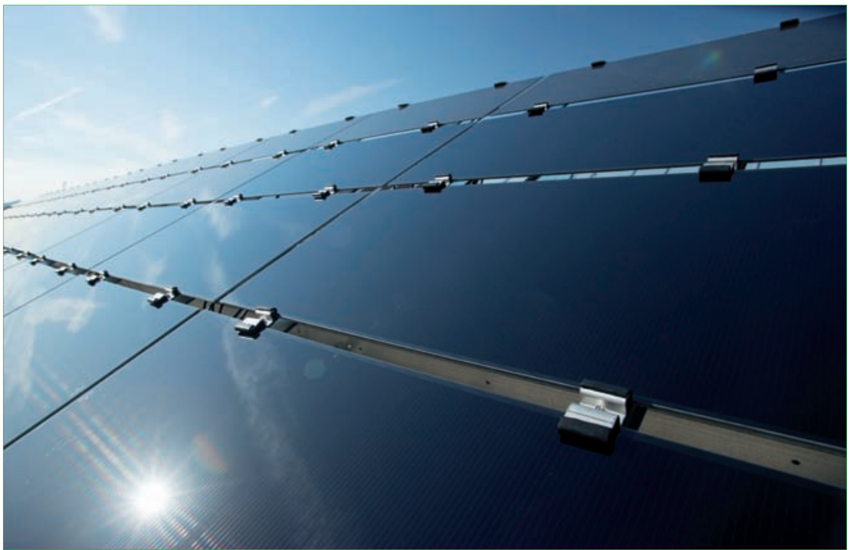
US asks WTO to investigate India solar procurement rules

The US government has requested that the WTO investigate India's domestic content requirements that form part of its solar procurement drive.

US Trade Representative Michael Froman has referred the country's National Solar Mission to the WTO in reaction to its rules that some projects in the scheme must guarantee the use of domestic Indian components and labour.

Half of the latest 750MW round of bidding in the Indian procurement programme had a domestic content requirement attached. The rules apply to both thin-film and crystalline silicon technology.

While a number of other countries have established quotas or bonus tariffs for domestic content, including Canada, South Africa and France, the Indian policy has attracted the most attention from the US.



Source: First Solar.

First Solar looks set to miss out in India's latest solar bidding round.

CIGS efficiency conversion

NREL verifies 16.6 % conversion efficiency of CIGS thin-film lab module from Avancis

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

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

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

News

Source: NREL.

NREL has verified a 16.6% efficiency in an Avancis CIGS module.

Siva Power claims 18.8% lab CIGS efficiency

US-based start-up, Siva Power, formerly Solexant, has reported a CIGS cell efficiency of 18.8% that it claims was verified by NREL in December 2013.

The company has not provided further details on the cell dimensions or specifications, but touted that it had come close to equaling record cell efficiencies previously reported by the US NREL, the Swiss laboratory, EMPA and ZSW in Germany.

Siva Power noted that it employs a three-stage co-evaporation process that was also used for the majority of previous CIGS cell records.

Siva Power is targeting mass production of CIGS thin-film modules with sub-US$0.40 per watt costs.

Facilities & Projects

Tokyo Electron to close down former Oerlikon Solar thin-film operations

Tokyo Electron (TEL) has announced plans to discontinue its 'micromorph' turnkey thin-film production line operations, which it acquired after buying Oerlikon Solar in 2012. Tokyo Electron, which recently announced a merger with major technology equipment rival Applied Materials, had also played in the a-Si thin-film turnkey market until withdrawing from the sector. The former Oerlikon Solar operations, based in Trübbach, St. Gallen, Switzerland and TEL Solar Technology Center Tsukuba, in Ibaraki, Japan will be downsized with expected job losses and will operate to support existing customers only. The company said that the business environment remained weak for the solar manufacturing sector, due to the oversupply of production equipment.

Solopower claims new finance could re-open shuttered thin-film factory

Thin-film manufacturer Solopower has announced that it is close to reopening its factory in Portland, Oregon.

The firm claims to be finalising an agreement with new investors that will allow it to re-staff the facility that has remained largely idle since last year. It has arranged a round of interim financing as the first stage of that process.

Earlier this week a deadline passed on a debt owed to Oregon's department of energy. It was unclear whether the remaining sum, in excess of US$100,000, had been paid within the five day grace period that followed the 1 February deadline

Hanergy Solar to start building 3GW CIGS thin-film manufacturing complex in China

Hanergy Solar has said it will start construction of a planned 3GW CIGS thin-film manufacturing complex in Caofeidian, Hebei Province, China in March 2014 with tool install starting by the end of the year. Hanergy Solar is establishing a subsidiary, Hebei Caofeidian Hanergy Photovoltaic Co. Ltd, to own and operate the new complex. Initial plans are to build two separate production lines with a total nameplate capacity of 600MW. Hanergy Solar said one of the turnkey lines with a nameplate capacity of 300MW would employ MiaSolé-based CIGS sputtering process technology, while the second line with a further 300MW would employ Solibro's co-evaporating manufacturing process technology. Both CIGS manufacturers were acquired by Hanergy Group and their technology licenses transferred to Hanergy Solar and subsidiaries. The initial 600MW phase-one construction and equipment spending is estimated at approximately US$780 million. Hanergy Solar is banking on both CIGS technologies providing the highest conversion efficiencies of any thin-film technology, while the large-scale operation would provide the lowest manufacturing costs, enabling CIGS technology to become a major mainstream technology and position Hanergy Solar as the leading global CIGS supplier.

US government approves 550MW of First Solar projects

The Department of Interior has approved 550MW of First Solar PV projects to be sited on public land. The 300MW Stateline Solar Farm Project in San Bernardino County, California, will cover 682 hectares and will create 400 jobs during construction. The 250MW Silver State South Solar Project in Nevada will cover 971 hectares. First Solar cut the size of the Silver State South project by 100MW in order to attain approval and has committed nearly US$7 million to programmes to protect the Desert Tortoise. Cooperation of federal, state and local agencies with the Bureau of

Source: Oerlikon

Tokyo Electron is to discontinue the former Oerlikon Solar thin-film operations.

Land Management was required for environmental approval. Southern California Edison has signed a 20-year PPA for the plants.


Source: First Solar.

First Solar has won approval for 550MW of projects on public land in the US.

Research and development

LPKF SolarQuipment upgrades Shanghai facility for thin-film laser scribing development

Laser structuring specialist, LPKF SolarQuipment has installed a new LPKF Presto laser scriber at its Shanghai application centre to extend its capabilities in researching advanced laser machining techniques for thin-film PV modules employing different coating technologies. The multi-function scribing system, designed for laboratory applications will be for scribing thin-film coatings of CdTe, aSi/µSi and CIGS, according to the company. The LPKF Presto system can be equipped with various laser sources and a mechanical needle. It has said that the system was developed to handle all the steps in the laser structuring of thin-film substrates such as scribing the pattern in P1, P2 and P3. In addition, the system design was said to enable both scribing of the coated surface as well as through the glass substrate. An integrated imaging system was said to be used to reference the P1 pattern for the P2 and P3 scribing steps. The Shanghai-based application centre was said to be ready to take customer samples for development.

South African R&D centre starts CIGS thin-film pilot line

PTiP (Photovoltaic Technology Intellectual Property), a spin-off from the University of Johannesburg (UJ) has commissioned its CIGS thin-film solar module pilot line in collaboration with equipment supplier, Singulus Technologies. The facility in the Techno Park near Stellenbosch, South Africa is designed to serve as a state-of-the-art research and development facility for commercial-scale (1200mm x 600mm) CIGS modules that take advantage of the climate and technology benefits, such as temperature co-efficiency and low-light conditions in the location. PTiP aims to supply CIGS modules with high local content to planned and future PV projects in South Africa.

Degradation studies of aluminium-doped zinc oxide

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ABSTRACT
This paper describes the degradation of sputtered aluminium-doped zinc oxide (ZnO:Al) layers which were exposed to damp heat (85°C/85% relative humidity). The ZnO:Al samples were characterized by electrical, compositional and optical measurements before, during and after damp heat exposure. Hall measurements showed that the carrier concentration stayed constant, while the mobility decreased and the overall resistivity thus increased. This mobility decrease can be explained by the enhancement of the potential barriers at the grain boundaries because of the occurrence of additional electron-trapping sites. X-ray diffraction (XRD) and optical measurements demonstrated that the crystal structure and transmission in the range 300–1100nm did not change, thereby confirming that the bulk structure stayed constant. Depth profiling showed that the increase of the potential barriers was caused by the diffusion of H_2O/OH^- through the grain boundaries, leading to adsorption of these species or to the formation of $Zn(OH)_2$ or similar species. Depth profiling also revealed the presence of carbon, chloride and sulphide in the top layer, which indicates the possible presence of $Zn_5(CO_3)_2(OH)_6$, $Zn_5(OH)_8Cl_2{\bullet}H_2O$ and $Zn_4SO_4(OH)_6{\bullet}nH_2O$. Furthermore, white spots appeared on the ZnO:Al surface during damp heat exposure. The spots contained elements, such as silicon and calcium, which might have migrated from the glass and which reacted with species from the environment, including oxygen, carbon and chlorine.

Introduction

Zinc oxide (ZnO) has been investigated extensively because of the increasing number of possible industrial applications, including gas sensors, transparent electronics and thin-film solar cells. For chalcopyrite-based thin-film PV – such as $Cu(In,Ga)Se_2$ (CIGS) solar cells – aluminium-doped ZnO (ZnO:Al) is used as a front contact, as it is a non-toxic, inexpensive and abundant material. Furthermore, ZnO:Al is very attractive for CIGS, since sputtering allows room temperature deposition, which prevents exposure of the underlying layers to elevated temperatures.

> "ZnO:Al is one of the key parameters in solar panel degradation."

Knowledge about ZnO:Al degradation is very important in the PV market, where producers give out warranties that panels will still yield 80% of their initial power after 25 years. CIGS PV should therefore be reliable for at least this length of time; however, it has been observed in field testing that CIGS PV often degrades too fast. It was discovered that ZnO:Al is one of the key parameters in solar panel degradation, indicating that the optical and electrical properties of ZnO:Al are not stable for 25 years in the field. Accelerated lifetime testing has demonstrated that water ingress leads to an increase in lateral sheet resistance of the ZnO:Al [1], thereby increasing series resistance in the solar cell; this results in a decrease in fill factor and consequently in efficiency.

Adequate encapsulation can protect solar cells against water ingress. For rigid modules, glass is an excellent encapsulation material, while for flexible modules, expensive inorganic/organic multi-stack materials are often chosen. A CIGS cell with a more stable ZnO:Al front contact can contribute to lower energy costs and accelerate the introduction of flexible CIGS modules to the market. Similar cost and lifetime issues are naturally important for other applications of ZnO:Al. It is therefore necessary to understand and improve the degradation behaviour of ZnO:Al when subject to water ingress.

In order to learn more about the degradation behaviour of ZnO:Al, several studies [2–7] have already tried to simulate exposure in the field, by placing the samples in damp heat conditions (1000 hours' exposure to 85°C/85% relative humidity RH). Some of these studies [2,3] have led to an increased insight into the change in electrical and optical properties caused by degradation. Relationships between these properties and the surface roughness of the substrate [2], deposition temperatures [4], crystallinity [4] and aluminium content [3] have been reported.

Various studies have also provided us with information about the change in the chemical composition of ZnO:Al – it has been suggested that the presence of oxygen along with water promotes ZnO degradation [5], while it is thought that the formation of $Al(OH)_3$ [2,7] and $Zn(OH)_2$ [2,6,7] plays a role in the degradation, since these materials do not conduct electricity. In general, however, although those studies provide an excellent physical picture of the degradation, the chemical behaviour is underexposed and does not yield an unambiguous picture for the influence of layer composition on the film properties.

Many questions about the degradation mechanisms of ZnO:Al therefore still remain unanswered. In order to learn more about the chemical and physical degradation behaviour of ZnO:Al, samples for this study were also submitted to damp heat, and their electrical, compositional and optical characteristics were analysed before, during and after degradation. This information was then used to define the degradation mechanisms in ZnO:Al, knowledge of which can help towards developing more stable ZnO:Al layers.

Full details about the study reported in this paper can be found in Theelen et al. [8].

Samples and degradation conditions

The deposition temperature of the degraded samples was varied: one sample was not intentionally heated, as is mostly the case for CIGS cells (room temperature or 'RT' sample), while another sample was deposited on a substrate heated to 200°C ('200°C' sample), thus reaching the maximal temperature acceptable for deposition on top of a CIGS/CdS stack. These samples allowed us to look at the broadest possible deposition spectrum.

The main differences between the RT and 200°C samples could be found in the thicknesses (620 and 490nm respectively) and grain sizes (0.9 and 1.3µm^2 respectively, measured from the top).

The samples were exposed to 85°C/85% RH for up to 2876 hours. Unless otherwise mentioned, the analyses after degradation were carried out after this period.

Structural and visual changes

In general, no changes in structural properties due to degradation were observed. The grain size and sample thickness, as measured by cross-section helium ion microscopy (HIM), were constant, while X-ray diffraction (XRD) measurements did not show major changes in structural properties as a result of degradation.

> "No changes in structural properties due to degradation were observed."

Visual changes, however, were observed on the surface: optical microscopy and scanning electron microscopy (SEM) revealed small dots and larger stains on the surface (Fig. 1), which increased in size and quantity with exposure time. After approximately 2000 hours, the circle-like dots had diameters of up to 100µm, while the stains, with less defined shapes, had diameters of up to 1mm. After 2182 hours, these blemishes covered approximately 6±1% of the surface.

The nature of these spots was studied by energy-dispersive X-ray (EDX) spectroscopy mapping at 10kV. Naturally, the elements zinc, oxygen and aluminium were encountered, but the less expected elements carbon, silicon and calcium were also observed. The spots and stains seem to consist of mostly calcium and carbon, but oxygen, silicon and aluminium were certainly also present, whereas the zinc has disappeared from these spots.

The distilled water was tested for cations by induced coupled plasma-mass spectrometer (ICP-MS) and showed only the presence of very small quantities of sodium and silicon, and no trace of aluminium and calcium. It is known that aluminium, silicon and calcium can be present in the glass, so these elements might have migrated from it. These migrating cations can be expected to react with H_2O, CO_2 or O_2 from the glass to form carbonates or hydrates. It is proposed that the spots and stains occur when the samples are removed from the climate chamber. The thin water film on the surface can then dry out and form small dots or coffee stains and leave behind salts.

Changes in electrical properties

Hall measurements showed that both ZnO:Al film samples exhibited an n-type behaviour, which is in agreement with the type of conduction associated with these ZnO:Al semiconductors. Fig. 2 illustrates the evolution of the resistivity of the two samples with degradation time. It was observed that the 200°C sample had an initial resistivity of $6\times10^{-4}\Omega$cm, which is a factor of two lower than that of the RT sample. The deterioration of the RT sample was also faster after exposure to 85°C/85% RH, and is therefore more vulnerable to damp heat.

A square-root function of the following form can be fitted to the increase in resistivity of both samples:

$$y = a \times \sqrt{(bt)} + c \qquad (1)$$

As a result, the conductivity automatically follows a $1/\sqrt{(t)}$ trend. The resistivity change can therefore be linked to a diffusion-like process, in which a species from an infinite reservoir diffuses into a semi-porous material. The diffusion of the species in the sample will hence be the rate-determining step, while the reaction between the diffused species and the grain boundary atoms inside the sample is a faster process.

It has been reported in the literature that thick samples have a lower degradation rate than thin samples [4–6]. This is explained either by a diffusion-based degradation process that starts from the surface and gradually deepens into the layer [6], or by a difference in grain sizes or

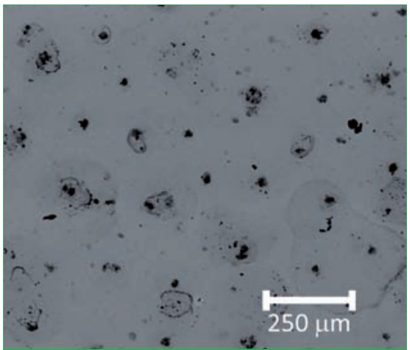

Figure 1. Backscattered SEM image of the RT sample after 2344 hours' exposure at 85°C/85% RH.

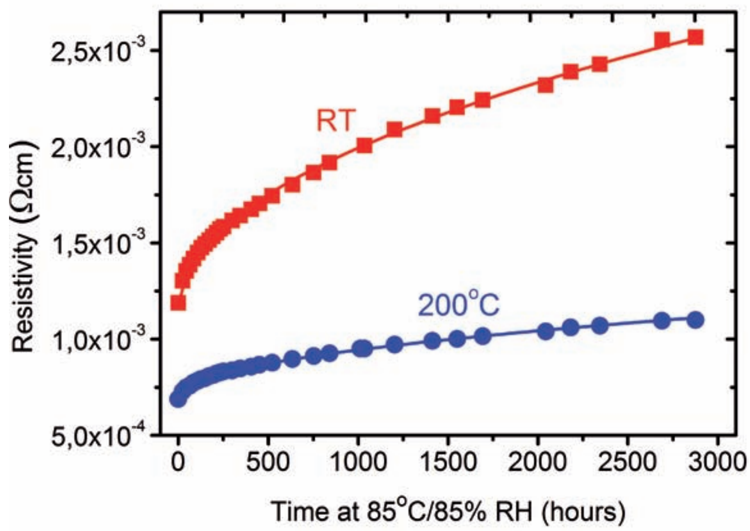

Figure 2. Evolution of the resistivity of the two ZnO:Al samples as a function of time, at 85°C/85% RH, as obtained by Hall measurements.

structures for different thicknesses [5]. In the study reported in this paper, it was confirmed that diffusion controls the resistivity increase.

The difference in resistivity increase between the 200°C and RT samples cannot be explained purely by the difference in thickness, since the samples were respectively 490 and 620nm thick, which cannot account for the large difference in the rate of increase in resistivity. It is therefore proposed that the diffusion rate can be explained by the number of diffusion channels present, for example the grain boundaries.

The Hall mobility and carrier concentration were also measured (Fig. 3). The initial values of both parameters were higher for the 200°C sample than for the RT sample. The mobility measurement for the 200°C sample was $20cm^2V^{-1}s^{-1}$, whereas it was $16cm^2V^{-1}s^{-1}$ for the RT sample; initial carrier concentrations of approximately $4.5\times10^{20}cm^{-1}$ and $3\times10^{20}cm^{-1}$ were measured for the 200°C and RT samples respectively. These values are in line with those reported in the literature [9].

When the influence of damp heat exposure was studied, a clear change in carrier concentration as a function of exposure time was not visible. The initial and final values of the carrier concentration after degradation only showed a very small decrease, which is within the error margin. It can therefore be concluded that the change in carrier concentration cannot be a major source of the increase in resistivity, which indicates that the bulk of the ZnO:Al grains has a constant composition.

On the other hand, the Hall mobility decreased during the first 1000 hours, but after that time point, the continued decline was slower. This decrease cannot be explained by the white spots, since these mainly occur at the top of the ZnO:Al layer, which will not block lateral electron movement. Furthermore, the size of the spots is a factor of 1000 greater than the grain size, so any influence on the electrical properties would also affect the carrier concentration. The reason for the decrease in mobility should therefore be found within the ZnO:Al layer itself.

Fig. 4 shows the dominant electron-scattering mechanisms in ZnO:Al that limit the mobility, i.e. the potential barriers at the grain boundaries and the ionized impurity scattering in the grains. In the case of the Hall measurements, electrons travel macroscopic lengths and cross several grain boundaries, so the grain boundary density can be a limiting factor of the value of the Hall mobility [10].

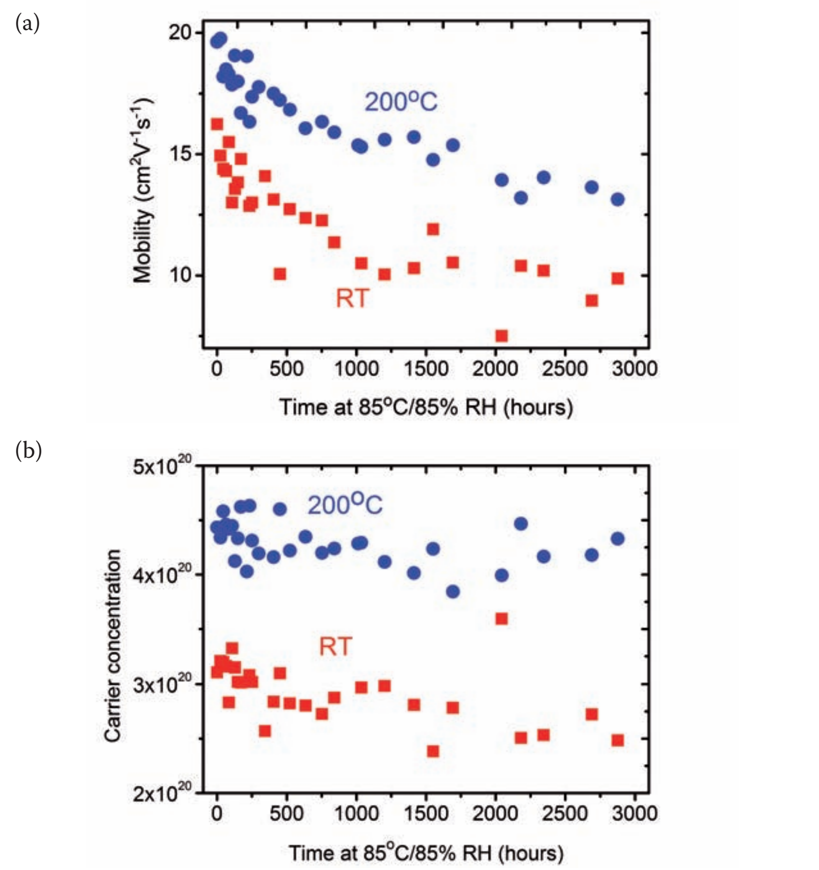

Figure 3. Hall mobility (a) and carrier concentration (b) of ZnO:Al as a function of time, at 85°C/85% RH.

"It can be expected that the formation of detrimental compounds in ZnO:Al occurs at the grain boundaries and not in the bulk material."

On the basis of the stable carrier concentration and the decreasing mobility, it can be expected that the formation of detrimental compounds in ZnO:Al occurs at the grain boundaries and not in the bulk material. Since the grain size for the RT sample is smaller than that for the 200°C sample, more grain boundaries are present in the former: degradation therefore occurs more quickly in the RT samples.

Changes in optical properties

The optical properties were studied by ultraviolet-visible (UV-VIS) spectroscopy and are shown in Fig. 5 for the RT sample (the 200°C shows a similar behaviour). Initially, the samples including glass transmitted 81% and 84% of the light for the RT and the 200°C samples respectively. During degradation, in the measured wavelength region (240–2400nm) the average transmission barely changed

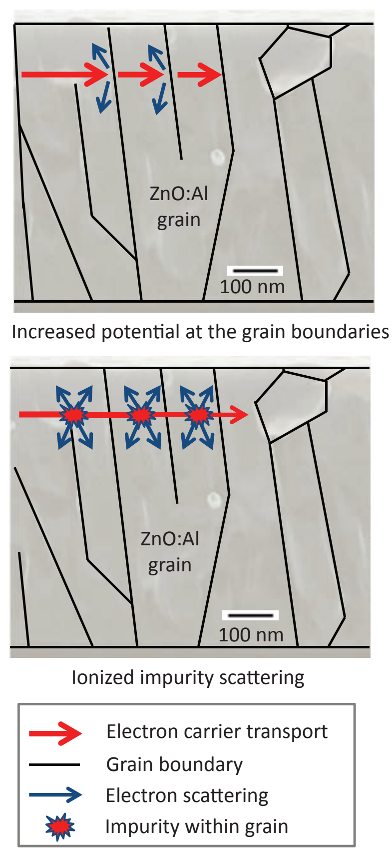

Figure 4. Possible scattering mechanisms in ZnO samples (based on Steinhauser et al. [10]).

with time. The constant plasma frequency and transmission in both the near-infrared and ultraviolet regions implies that the carrier concentration is constant in the bulk of the film, as was also concluded from the Hall measurements [11].

The only changes observed were a small drop in reflection and a small increase in absorption in the near-infrared region. These changes might be explained by the white spots, which might absorb some of the near-infrared light.

Within the highly transparent region, the measured spectra demonstrate an oscillatory behaviour, which is caused by interference effects due to multiple internal reflections of the incoming light in the ZnO:Al layer. Since the degradation did not influence this behaviour, no texturing or reduction of ZnO to Zn has occurred.

Changes in composition

The composition as a function of depth was measured by negative mode time-of-flight secondary ion mass spectroscopy (ToF-SIMS) through the layer before and after degradation. The depth profiles of the RT sample are shown in Fig. 6: these graphs show the difference in concentration of various important ions within the depth of the layers, as well as the impact of degradation. It should be noted that the concentrations depend on the ionization probability of the atoms and molecules, which varies per species and per background material. Therefore, no absolute concentrations are obtained in this study.

The ToF-SIMS depth profiling showed that the damp heat exposure introduced hydroxides, chlorine, sulphur and carbon into the film. The hydroxyl profile decayed by about one order of magnitude in the depth range 300–500nm, and it was higher everywhere than before degradation. When the RT sample was compared with the 200°C sample, it was observed that the hydroxyl profile for the RT film had a slightly higher maximum value, which indicated that more water had diffused into this sample. This can be explained by the higher number of grain boundaries.

Looking now at the bottom 300nm of the layer, the OH^- and H^- concentrations were found to be lower than in the top layer, indicating that the diffusion and thus the degradation can develop still further. In addition, there was a large amount of Cl^- in the films after degradation, which decreased by one order of magnitude in the depth range 100–200nm. In the region near the surface, the concentration of Cl^- is probably comparable with the hydroxide concentration, assuming that the ionization probabilities of OH^- and Cl^- in ZnO:Al are similar. Degradation thus induces a relatively high concentration of Cl^- in the top layers of the samples. Similarly, there was a slightly increased sulphur signal in the top 200nm after degradation, which was visible in the cross-section mappings as a very thin surface layer; the sulphur is probably present as sulphite or sulphate (SO_3^{2-} or SO_4^{2-}). Since ToF-SIMS does not provide absolute concentration, and chlorine and sulphur were barely detected by EDX, the total amount of these species in ZnO:Al is most likely very low. The treatment thus only induces these species near the surface of degraded ZnO:Al.

The C^- signal is only significantly raised in the top 100nm of the film as a result of damp heat exposure. The carbon concentration is difficult to estimate, because the C^- ionization probability is usually much lower than that of OH^- and Cl^-, but the

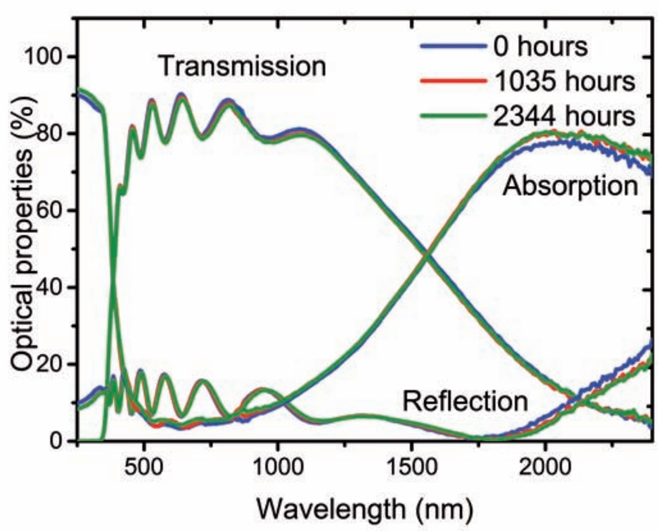

Figure 5. Evolution of the optical properties of the RT sample before and after exposure to 85°C/85% RH.

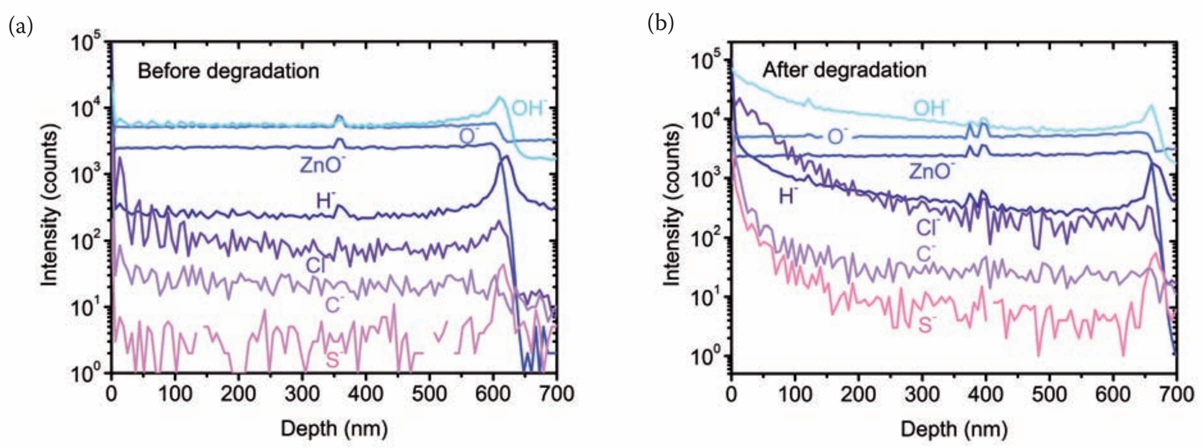

Figure 6. SIMS depth profiles of the RT sample before (a) and after (b) exposure to 85°C/85% RH. The depth profiles show the composition from the air–ZnO:Al interface (left of graph) to the ZnO:Al–glass interface (right of graph).

concentrations in the bulk are quite likely low. The chemical state of the carbon cannot be easily determined from a depth profile in an oxide film, but it might be (bi-)carbonate.

The O^- concentration did not change because of degradation and is completely stable as a function of depth, so it is unlikely that adsorption of O_2 is the main reason for ZnO:Al deterioration.

Since the complete thickness of the ZnO:Al layer is used for lateral transport of the electrons, it can be assumed that the impact of the surface element on the electrical properties is small. The main cause of the decrease in conductivity can therefore be found in the presence of $ZnOH^-$ and OH^-, which is present in the entire layer.

Degradation reactions

When considering the observed results, the following conclusions on physical and chemical changes in ZnO:Al due to damp heat treatment can be drawn:

- The three-dimensional structure of the samples stayed intact. The grain size and the thickness of the layers did not change with damp heat treatment.

- The main visual change was the appearance of white spots containing elements – such as calcium and silicon – which had migrated from the glass and reacted with elements, including oxygen and carbon, from the environment. These spots had a small influence on the absorption of light in the near-infrared region, but did not have an impact on the electrical properties or the overall transmission. The optical properties were also constant.

- The resistivity increased, mainly driven by a large drop in the Hall mobility, whereas the carrier concentration stayed constant. This implies the formation of a potential barrier in the grain boundaries.

- Chlorine, sulphur and carbon are present near the surface of degraded ZnO:Al, whereas OH^- is present in the bulk of the entire samples.

"The grain size and the thickness of the layers did not change with damp heat treatment."

Reactions in the grain boundaries

On the basis of these observations, it is concluded that the diffusion of species into the grain boundaries is the main cause of degradation. Water plays a significant role in the degradation; however, on the basis of the constant oxygen concentration in the ToF-SIMS depth profiling and of preliminary experiments on the impact of atmospheric species, a large role for oxygen is not suggested. On the other hand, a role for carbon dioxide is suggested. The impact of oxygen and carbon dioxide was found in a study by Theelen et al. [12]: ZnO:Al samples were exposed to water that was purged with air (mainly consisting of oxygen, nitrogen and carbon dioxide), which led to fast degradation. Purging with pure nitrogen and oxygen, on the other hand, only induced very slow degradation. It is therefore concluded that the reactivity of carbon dioxide in combination with water is much larger than the impact of oxygen. The impact of carbon dioxide, which is omnipresent in the atmosphere, should thus not be underestimated [12]. Since chlorine and sulphur were also encountered in the degraded ZnO, a role for these materials is also proposed.

When the nature of the reactions occurring in the grain boundaries is considered, the diffusion of the degrading species can influence the resistivity in two ways, which are not easily distinguishable:

1. Molecular adsorption (physical reaction)

2. Chemical reaction

A combination of molecular adsorption and chemical reaction is the most likely scenario. This can also be inferred from the reversibility experiments in Tohsophon et al. [13], where both a change in resistivity when annealing at 150°C and an effusion of water, CO_2 and H_2 at higher temperatures (around 500°C) was reported. This indicates the involvement of two different phenomena.

Molecular adsorption

When the molecules are adsorbed at the grain boundaries or at the surface, electron traps can be formed. ZnO is known to have excellent H_2, CO and CO_2 absorptivity after being cleaned of absorbed H_2O and CO_2 by vacuum heating [14]. It is proposed that H_2O can be adsorbed at the grain boundaries, on the basis of the fact that OH^- and H^- were encountered.

Chemical reactions

Chemical degradation begins with the presence of unbound zinc, oxygen or aluminium species. These species can be present either because of dangling bonds or defects, or because of the dissolution of ZnO:Al in the thin water film present at the surface and possibly in the grain boundaries. Both chemical and electrochemical dissolution of ZnO can result in the formation of a Zn^{2+} cation. Electrochemical reactions depend on the electrode potential, which regulates the absorption of protons at the surface. This situation is not expected in these experiments, but might occur in solar cells, which are electrically active.

Whether ZnO dissolves in an aqueous solution is mainly a function of the acidity. It is thermodynamically

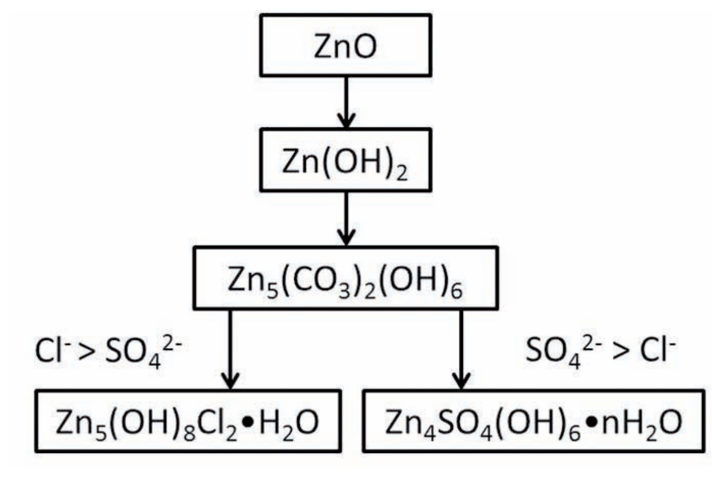

Figure 7. General reaction scheme for the degradation of ZnO (based on Odnevall & Leygraf [15]).

stable in the pH range of 6 to 12, but can dissolve in solutions with a higher or lower pH [14]:

$$ZnO(s) + 2H^+(aq) \rightarrow Zn^{2+}(aq) + H_2O(l) \quad \text{(chemical dissolution)} \qquad (2)$$

ZnO can also dissolve under certain conditions as a result of illumination. After Zn^{2+} formation, this ion can either wash away with the water or react with other species. In this study, the layers kept the same structural characteristics, so it is unlikely that Zn^{2+} had disappeared from the samples.

More information about the nature of the species formed in the grain boundaries is available in the literature and by calculations. The first hint of possibly stable reaction products of ZnO degradation can be found in nature: in exposed deposits, most of the mined zinc compounds are sulphides, carbonates and hydrocarbonates.

The reaction products of zinc compounds in nature have already been described in the literature [14]; it has been shown that there are large amounts of reaction products occurring in nature, and that there is the possibility of multiple corrosion products being present in the same place. Although ZnO:Al is naturally a different material to pure Zn, it can be assumed that several of its reaction products should be similar.

Odnevall & Leygraf [15] propose the formation of the major corrosion products of zinc under sheltered conditions and show a reaction sequence from zinc hydroxide, via hydroxycarbonates, to chlorides and sulphates, as shown in Fig. 7.

Goux et al. [16] showed experimentally that $Zn(OH)_2$ is kinetically favoured at low temperatures (under 34°C) and can thus also be formed according to:

$$Zn^{2+} + 2OH^- \rightarrow Zn(OH)_2 \qquad (3)$$

This species can react further in the presence of CO_2 to hydrozincite:

$$Zn(OH)_2\,(s) + 4Zn^{2+}\,(aq) + 4OH^-\,(aq) + 2CO_3^{2-}\,(aq) \rightarrow Zn_5(CO_3)_2(OH)_6\,(s) \qquad (4)$$

In the presence of Cl^- and SO_4^{2-} ions, the hydrozincite can be replaced. Subsequent steps might lead to the formation of compounds containing sodium and of products containing both sulphate and chlorine. The species as shown in Fig. 7 have most likely formed in the grain boundaries, where they function as a potential barrier.

Since carbon and sulphur are mainly found at the top of the samples in the ToF-SIMS measurements, it is expected that the hydroxycarbonate – e.g. $Zn_5(CO_3)_2(OH)_6$) – and the hydroxysulphate – $Zn_4SO_4(OH)_6{\bullet}nH_2O$ – are surface compounds. However, the chloride compounds – e.g. $Zn_5(OH)_8Cl_2{\bullet}H_2O$ – and the hydroxide-containing species will be present in a larger portion of the sample and will therefore have a greater impact on the change in the electrical parameters.

> "Species from the glass as well as from the environment migrate through the ZnO:Al."

Degradation mechanism based on the migration of species

The results have demonstrated that species from the glass as well as from the environment migrate through the ZnO:Al. It is therefore proposed that migration occurs in two directions (Fig. 8): the downward diffusion (blue arrow) leads to an increased resistivity, while the upward migration (green arrow) does not seem to influence the electronic properties. However, the impact of this migration on the optical properties is minor.

We propose that the degradation in ZnO:Al occurs in the following steps:

1. (a) Small molecules – such as water, carbon dioxide, sulphur species and chloride species – diffuse from the environment into the grain boundaries.

   (b) Small elements – such as calcium, silicon and aluminium – leach from the glass and enter the grain boundaries.

2. (a) The small molecules react with or adsorb to the grain boundaries, which results in an increase in potential barriers and thus a decrease in mobility. The rate of this reaction is determined by diffusion and differs by species. The hydroxide-based elements have the highest diffusion rate.

   (b) Calcium, silicon and aluminium reach the ZnO surface.

3. (a) Once the grain boundaries are saturated with hydroxides, the decrease in mobility slows down.

   (b) Spots and stains form as a result of the reactions of calcium, silicon and aluminium with carbon and oxygen from the environment. When the samples are removed from the climate chamber, drying stains are formed because of the evaporation of residual moisture at the surface.

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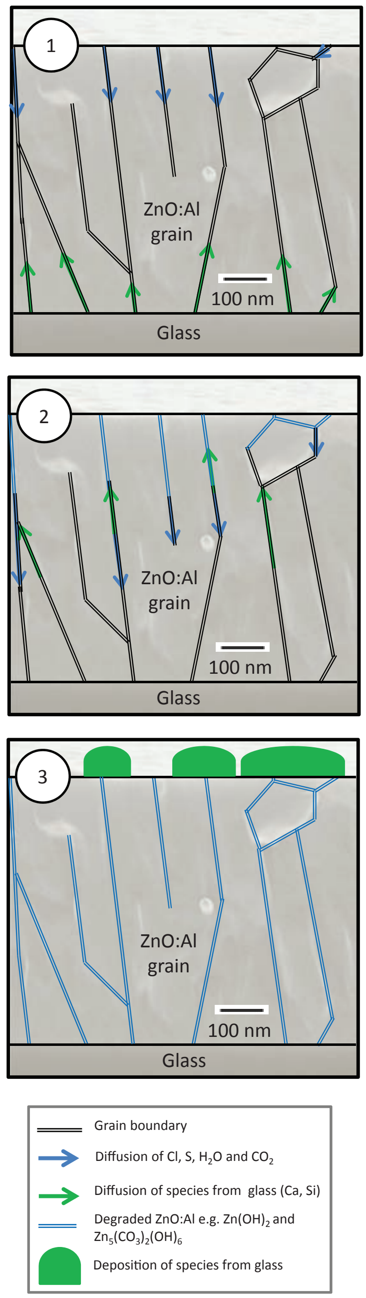

Figure 8. Proposed degradation mechanism for ZnO:Al layers.

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About the Authors

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Zeger Vroon studied chemistry and received his Ph.D. from the University of Twente in the Netherlands, on the subject of ceramic membranes. He began working at TNO in 1995, where he was involved with the preparation of inorganic and hybrid coatings by sol-gel processing. Since 2008 his work has focused on reliability, light management and integration in solar cells. Zeger has held a lecturer position at Zuyd University of Applied Sciences in Heerlen since 2009.

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Miro Zeman has been a full professor at Delft University of Technology in the field of photovoltaic materials and devices since 2009. He is a leading expert on light management, modelling, and novel materials and nanostructures in thin solar cells. He has authored and co-authored 200 articles and contributed to five scientific books.

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PV Modules

News

Ford using SunPower cells for plug-in hybrid concept car

Car maker Ford is looking at employing a static canopy using solar concentrator lenses to boost recharging. The system uses autonomous car technology to move the car underneath the canopy to optimise conversion efficiencies and reduce battery recharging times. Although solar cells integrated into a car's roof is not a new concept, the combination of an off-grid Fresnel lens canopy to boost cell efficiency and potentially remain off grid for charging certainly is. The Ford 'C-MAX Solar Energi' concept car employs SunPower's 'Maxeon' high-performance cells but as with most embedded automotive roof PV systems is insufficient in size to provide meaningful battery recharging. The off-grid solution is said to draw enough power in a day to equal a four-hour battery charge (8 kilowatts). However, the vehicle still retains a charge port, so that drivers can recharge via the grid.

Ford is using SunPower cells for its plug-in hybrid concept car.

Source: Ford.

Technology

Vikram Solar considering MWT solar cell technology from Cencorp

India-based PV manufacturer, Vikram Solar, is considering a technology collaboration with Finish firm Cencorp in respect to its metal wrap through (MWT) solar cell and conductive back sheet (CBS) based PV module technology.

According to Cencorp, both parties have a signed a 'term sheet' for six months from 7 February 2014 to further discussion in respect to the technology and business issues surrounding due diligence.

Cencorp assembled its first PV module with conductive back sheet material as part of a plan to offer the technology to PV manufacturers back in May 2013. In 2012, the company acquired the conductive backsheet business unit of Avery Dennison and Sunweb Solar Energy's IP related to MWT and a related pilot production line.

Vikram Solar has around 150MW of nameplate module capacity in India.

Trina Solar's smart module used in first US project

Trina Solar's 'Trinasmart' PV module using Tigo Energy's impedance-matching optimizer technology has been deployed for the first time in the US.

PV system installer Cobalt Power used 462 Trinasmart 245W modules on a 113kW commercial rooftop project in the San Francisco Bay Area.

The customer used the smart modules to gain around 3% higher power output than from conventional modules due the plan to build a net zero energy office building from the available rooftop space. The system is monitored by Tigo Energy's software engine.

Lightsource employs 'first' mobile module testing lab on UK PV project

UK-based solar energy generator Lightsource Renewable Energy, has used what is thought to be the first mobile PV testing laboratory in the world on its recently acquired 5MW power plant in Cornwall, England.

Lightsource teamed up with Spanish PV engineering consultancy, Enertis Solar, which developed the unit, to conduct a range of tests on the China Sunergy-built project.

Tests included visual inspection, peak power measurement (Flash Test), isolation tests as well as electroluminescence test and inspection and thermal imaging testing. According to Enertis Solar, all such tests can be performed to IEC 61215 and IEC 61646 standards.

Rulings & Regulations

US ITC votes to proceed with latest SolarWorld trade case

The US International Trade Commission (ITC) has ruled that an investigation into anti-dumping and countervailing duties for solar cell products from China and Taiwan will go ahead, following a preliminary phase vote in Washington DC in mid-February.

The most recent complaint brought by manufacturer SolarWorld focused on the alleged practice of companies circumventing duties on cells produced in China by using facilities in Taiwan.

As a result of the US ITC preliminary determinations, the US Department

Lightsource has used what is said to be the world's first mobile PV testing laboratory in the UK.

Source: Lightsource Renewable Energy.

Source: SolarWorld.

SolarWorld's latest trade complaint has been upheld in the US.

of Commerce is expected to continue its investigations on imports, with a preliminary countervailing duty determination due on or around 26 March 2014 and antidumping duty determinations due on or about around 9 June 2014.

Waste management for PV modules in EU now mandatory

PV producers in Europe face significant changes to the way they handle waste solar modules after an EU-wide change of disposal rules went into effect.

As of 14 February, the European Waste Electrical and Electronic Equipment Directive (WEEE), governing the disposal of waste electrical equipment, including PV panels, must be applied as national law by every EU member state.

The full implementation of WEEE rules followed an 18-month implementation period from a 2012 WEEE directive revision to include PV panels.

The UK and Bulgaria were the first to enshrine the European directive WEEE regulation into national law before the deadline. So far, no other EU member state has implemented their national version of the European directive.

Ontario eliminates renewables' domestic content requirement

The government of Ontario is eliminating the domestic content requirement for renewable energy projects.

An amendment in the Ontario Electricity Act, which specified that 60% of a solar or wind project's equipment or services must be locally sourced, was ruled as unfairly discriminating against outside companies by the WTO. In May the domestic requirement level was reduced to 22% for crystalline and 28% for thin-film PV systems. Originally a temporary measure to resettle domestic trade, the requirement has been eliminated entirely. The government claims industry growth means it is no longer required and that the move will save ratepayers CA$1.9 billion over 35 years.

Company News

Dutch distributor Sunconnex files for insolvency

The Dutch PV distributor and installer Sunconnex has filed for insolvency, according to papers lodged with a court in Amsterdam in mid-February.

Sunconnex operates across Europe from Iceland to Turkey, as well as in the US and Philippines. Three Sunconnex businesses have registered for insolvency in total, Sunconnex BV, Sunconnex Projects BV and Sunconnex Distribution BV.

The court papers show a C.M. de Breet listed as the administrator for all three

Sunconnex businesses. The company had a US$189 million sales contract with Solyndra prior to the manufacturer's demise.

Suntech Power Holdings starts Chapter 15 proceedings in US

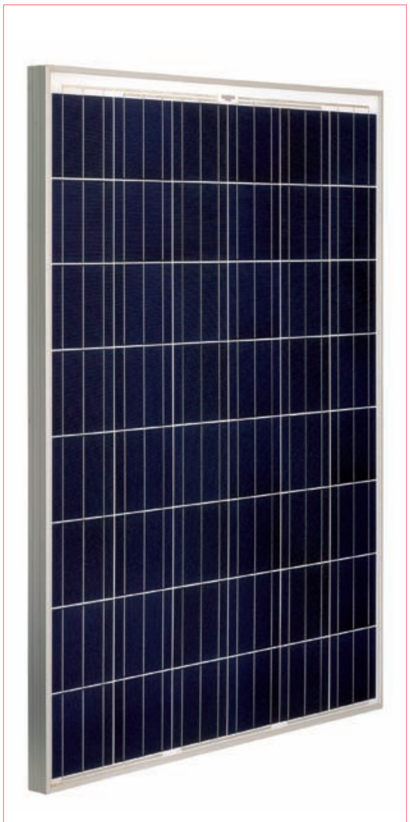
Suntech Power Holdings has officially started Chapter 15 proceedings in the US as it seeks protection from some of its bondholders already applying for the company to be forced in Chapter 7 bankruptcy proceedings, which would effectively dissolve the company.

Suntech Power Holdings' liquidators in the Cayman Islands, where the company is registered, said that the Chapter 15 application would consolidate proceedings as it attempts to conduct restructuring measures and at some stage provide creditors with some level of financial recompense. Suntech Power Holdings remains under the control of Suntech's founder and major shareholder, Dr Shi.

Aleo solar dodges bullet thanks to Bosch deal

Aleo solar has said it expects losses for 2013 exceeded half its share value triggering an extraordinary general meeting.

The company is still finalising its financial statement but has announced that it expects losses for the 2013 financial year to reach €100 million (US$136.7 million). Under German law, the company is obliged



Source: Aleo solar.

Aleo solar's deal with Bosch has been a lifeline.

to call a meeting of shareholders in the event that its losses pass the landmark of half its share capital.

Under additional conditions the company can then be subject to tighter financial restrictions but aleo says its arrangement with Bosch has seen off that threat.

Suntech subsidiaries clash in US$264 million court ruling

Suntech Singapore has been ordered to pay Suntech Power Holdings' immediate subsidiary Power Solar System (PSS) nearly US$264 million.

The court in Singapore made the award to PSS in early February after its liquidators claimed it was owed US$263,910,599 plus 5.33% interest and costs. Suntech Singapore did not respond within the given time frame and the ruling went against them.

The Japan and Singapore units existed alongside Wuxi Suntech as subsidiaries of PSS, which in turn had been a subsidiary of Suntech Power Holdings. The two were then rolled into Wuxi Suntech around the time that Shunfeng began its acquisition of Suntech's main manufacturing operation based in Wuxi. The exact nature and timing of the transfers remains in dispute.

Emerging Markets

Vikram Solar given tier one module manufacturer status

Indian PV module manufacturer Vikram Solar has been given tier one status.

The status means three non-development banks have funded projects using Vikram modules in the past two years, according to the criteria set out by Bloomberg New Energy Finance (BNEF).

"Despite the global consolidation of the solar market, there are still many module manufacturers," said Gyanesh Chaudhary, managing director, Vikram Solar.

Thai module manufacturer Solartron to double production

Thai PV manufacturer Solartron is planning to double its production capacity. The firm's CEO Patama Wongtoythong told the Bangkok Post that it was looking to expand its current module capacity from 70MW to 150MW.

The THB250 million (US$7.6 million) investment drive will be backed with the issuance of 150 million new shares.

The company claims to have a backlog of 60MW and its current facility is approaching capacity. It hopes to have the additional production line, which will be incorporated into its existing factory, online during 2015. The company will be holding talks with Chinese manufacturers in the first half of 2014 to discuss a partnership to enter the European and Japanese markets.

ReneSola eyes Africa expansion from new Cape Town base

Chinese PV manufacturer ReneSola has announced the opening of a new office in Cape Town, South Africa.

The regional office will serve as the headquarters for ReneSola's sales and marketing operations in Africa, which the company said it was looking to expand.

Qasim Abrahams, general manager of ReneSola South Africa, said the new office would serve as a gateway to markets in Ghana, Rwanda, Namibia and Kenya.

European Manufacturing

Module manufacturer asola to resume production

German module manufacturer asola is to resume production at its facility in Erfurt. The company was purchased by Chinese capacitor manufacturer STGCON in June and has since undergone restructuring.

Early signs indicated that module production would be outsourced from Germany to Croatia as the business shifted it focus to project development, storage and specialist installs such as car ports.

The move into storage systems alongside PV modules has been confirmed. The reopening will initially create 10 production jobs per shift.

Italian PV maker Waris signs distribution deal with Solarmarkt, doubles production capacity

Italian solar manufacturer Waris will double the production capacity of its manufacturing facility in Condino, following the signing of an agreement with distributor Solarmarkt Deutschland.

According to Waris the developments mark the beginning of internationalisation for the company, while it continues to strengthen its market presence in its Italian homeland.

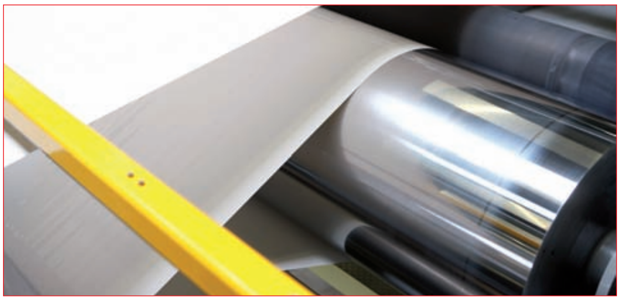
The multicrystalline module producer's 35MW facility in Trento, northern Italy, will see annual production capacity increase to 70MW.

Waris claims the jump in production capacity is part of a wider "general revamping" process for the facility and company. Around 60 employees will staff the expanded 70MW plant.

The exclusive agreement for sale and distribution of Waris modules through Solarmarkt covers the central European sales region, where Waris aims to sell

Product Reviews

Isovoltaic



Isovoltaic's 'ICOSOLAR' TPA HR backsheet offers harsh climate protection

Product Outline: Isovoltaic's recently introduced PV module backsheet combines both 'Tedlar' and 'Polyamide' materials to provide improved characteristics for field durability and enhanced module efficiency, especially in challenging conditions.

Problem: Solar cells require effective protection via the backsheet to be able to efficiently convert sunlight into useable energy. Adhesion values between the layers of the backsheet and from the backsheet to EVA are critical, as delamination can seriously reduce the module's service lifetime. The effective reflectivity of solar backsheets can also influence the conversion efficiency of a module.

Solution: ICOSOLAR TPA HR is claimed to provide both service lifetime through material selection and improved module efficiency through high reflectivity.

The unique resin formula has a background that is said to have already been in more than 25 years of use in TPT-backsheets like ICOSOLAR 2442. The latest rendition is said to assure layer adhesion that works after 3500 h damp heat testing, which is in line with previous formulations.

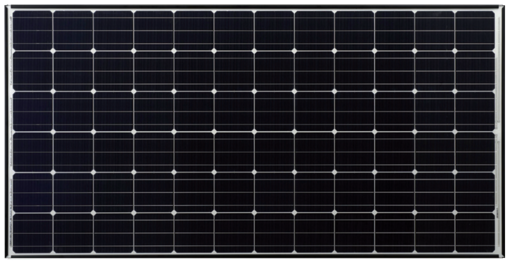
The addition of the special polyamide film on the cell side provides exceptionally high reflectivity and adhesion of up to 100 N/cm (measured by leading tier one module manufacturers). The field-proven Tedlar outer layer features high resistance to UV and weathering. The PET core provides mechanical stability, electrical insulation and a water vapor barrier.

Applications: c-Si PV module backsheets to protect solar cells, especially when used in challenging conditions.

Platform: Isovoltaic offers both proven TPT-composite films (ICOSOLAR 2442) and films based on polyamide (ICOSOLAR APA 3G), which is UL recognized and TÜV type approved and has already been certified by several module manufacturers for use in their modules.

Availability: Currently available.

Panasonic



Panasonic's upgraded HIT PV module available with 19.4% conversion efficiency

Product Outline: Panasonic has launched the 'HIT-N245' and 'HIT-N240' PV modules. The HIT-N245 module has a conversion efficiency of 19.4% and comes with several upgraded features intended to provide overall improved operational performance, notably for residential rooftop markets.

Problem: Lower feed-in tariffs across many European markets are increasing the need for high-performance modules to ensure adequate return on investment (ROI) for residential owners, while requiring high-quality products for longevity.

Solution: The new HIT modules are designed for residential rooftop applications that require high-performance and high quality PV modules for longevity.

With a module efficiency of 19.4% and a cell conversion efficiency of 22% the HIT-N245 ranks as one of the highest performing modules on the market. The company claims that the modules also have a very low temperature coefficient of negative 0.29%/°C, and therefore superior operating over conventional cells in normal operating conditions.

Applications: Residential rooftop.

Platform: The new HIT modules come with a special water-drainage frame: drainage lines in the module frame allow for constant discharging of accumulated water. As water is not allowed to dry on the module, there are no drying stains, and any build-up of humidity inside the panel is effectively prevented.

The water-drainage frames are also claimed to help to keep modules clean, even in low-angle installations. The modules are IEC 61285/61730 certified by JET and the company claims a very low 0.0039% of guarantee cases out of 3,309,916 solar modules produced for the European market (as of December 2013).

Availability: The upgraded HIT-N240 has been available since January and the new HIT-N245 will be available in Europe in spring 2014.

Advanced methods for determining PV module process optimization potential

Gernot Oreski, Polymer Competence Center Leoben GmbH, Leoben, Austria

ABSTRACT

Ethylene vinyl acetate (EVA) is still the dominant material used for encapsulation of solar cells. During PV module lamination, a three-dimensional network is formed by a chemical cross-linking of the polymer chains in order to increase the thermal stability of the material and to prevent the material from melting when exposed to application-relevant temperatures of up to 100°C. The cross-linking reaction, which is discontinuous and can take up to 30 min (depending on the EVA type), is the time-determining step in PV module lamination. The main objective of this paper is to gain a comprehensive understanding of the thermomechanical material behaviour during the PV module lamination process, and to develop a basis for the optimization of the PV module manufacturing process. The results presented will demonstrate that dynamic mechanical analysis (DMA) is a valuable and reliable characterization method for the investigation of the curing behaviour of EVA for solar cell encapsulation. DMA in shear mode allows a continuous measurement of the thermomechanical properties, even in the molten state, and therefore an in situ monitoring of the cross-linking reaction. Whereas it is possible to use temperature scans on partially cured EVA films to determine the state of cross-linking, isothermal scans on uncured samples allow the curing kinetics of EVA to be investigated. On the basis of an enhanced knowledge of the cross-linking reaction, the material-related process-parameter optimization potential of the PV module lamination process can be identified, and optimum processing temperature ranges and minimum cross-linking times can be derived.

Introduction

During the last few years the PV industry has seen remarkable growth. For these high growth rates to continue, and for additional market volumes and new fields of applications to be developed, investment in comprehensive R&D programmes is necessary. To achieve grid parity, and therefore to contribute to the overall power requirement, there needs to be in particular a significant reduction in costs. Achieving this cost reduction will depend not only on scale-up benefits, but also on the costs of the encapsulation materials and the PV module lamination process [1].

The main solar cell encapsulation material for PV modules is currently ethylene vinyl acetate (EVA) copolymer. The solar cell encapsulant has to fulfil several basic functions, which include providing structural support and physical isolation of the solar cells, maintaining electrical isolation, and being highly transparent in a selected spectral region, according to the cell technology used [2]. To deal with different thermal expansions of the materials (glass, solar cell, interconnects, polymers) used in a module, and to avoid over-stressing and cracking, the encapsulant material must have a low-modulus, elastomeric property. Furthermore, a maximum optical coupling between the solar cell and the incident solar irradiation in a prescribed spectral region, with an initial transmission of at least 90% and a loss of less than 5% after 20 years of module lifetime, has to be achieved.

EVA is a semi-crystalline copolymer of ethylene and vinyl acetate (VA); for PV applications, the VA content usually ranges from 28 to 33%. The thermal, mechanical and optical properties can vary over a broad range, depending on the VA content. Polyethylene copolymers are random copolymers that consist of linear ethylene sequences and regions with short-chain branches introduced by the co-monomers (e.g. VA, octane) [3,4]. The VA side groups of the EVA do not enter the crystalline regions, which can be attributed exclusively to the ethylene sequences. Both melting temperature and degree of crystallinity depend on the co-monomer content: the higher the VA content, the lower the melting temperature and degree of crystallinity [5]. Consequently, a higher VA content also leads to a higher mechanical flexibility of the polymers. Finally, the VA content also influences the optical properties, as the introduction of side groups to the ethylene chain reduces the degree of crystallinity and thus the light-scattering at the crystalline regions [6]. The melting temperature of PV-grade types of EVA is between 60 and 70°C, whereas the lamination temperature is around 150°C, depending on the peroxide curing agent that initiates the cross-linking reaction. During lamination, a three-dimensional network is formed by a chemical cross-linking of the polymer chains in order to increase the stability of the material and to prevent the material from melting when exposed to application-relevant temperatures of up to 100°C [2].

> "The degree of cross-linking is mainly controlled by the lamination temperature and the lamination time."

Apart from the concentration of the curing agent, the degree of cross-linking is mainly controlled by the lamination temperature and the lamination time. Previous studies have shown that dynamic mechanical analysis (DMA) in shear mode allows a continuous measurement of the thermomechanical properties, even in the molten state, and therefore an in situ monitoring of the cross-linking reaction [7–10]. A good correlation between DMA results and the Soxleth extraction test was also found. Furthermore, it was shown that DMA measurements yield the highest sensitivity and reproducibility as regards the first few minutes of the reaction [7]. Hence, the main aim of this paper is to gain a comprehensive understanding, by using DMA in shear mode, of the thermomechanical material behaviour during the PV module lamination process, and to establish a basis for the optimization of the PV module manufacturing process.

To meet the objectives, a systematic investigation of the influence of the cross-linking process on the thermomechanical properties of EVA films was undertaken. Two different DMA measurement and evaluation concepts were chosen and are presented in this paper. On the one hand, temperature scans were carried out on partially cross-linked EVA in order to examine the changes in the thermomechanical properties due to the cross-linking process. On the other hand, isothermal scans on uncured samples were performed in order to study the curing kinetics. Finally, the potential for lamination process optimization is then determined from the results obtained.

Experimental and materials

Two commercially available EVA encapsulation films from two different manufacturers were selected for the studies (Table 1).

To ensure realistic processing conditions, two uncured EVA films were laminated together between two release films and a glass plate and cured at 146°C in a PV module laminator (Incapcell 43–24, Spaleck-Stevens, Bocholt, D). The lamination processing cycle consisted of four phases: evacuation (500 sec), compression (310 sec), cross-linking (varied between 300 and 1200 sec) and ventilation (50 sec). To obtain different degrees of cross-linking, the cross-linking time was varied systematically between 300 and 1200 sec. Table 2 summarizes the variation of the cross-linking and total lamination times.

The thermomechanical analysis was performed by DMA using a Perkin Elmer DMA 8000. Measurements were taken on a circular specimen (9mm diameter) in shear mode. Temperature scans of uncured and partially cured samples were carried out between room temperature and 200°C at a heating rate of 3K/min. The isothermal characterization of uncured samples was done at temperatures of 130, 140, 150, 160 and 170°C. Sample displacement was set to 20μm and the test frequency to 1Hz.

The thermal analysis was carried out using a Mettler Toledo DSC 821e instrument. Two heating runs needed to be performed in order to compare the uncured with the cured material and to ensure that the whole cross-linking process had occurred. A circular sample disc was cut with a punch, placed in a 40μl pan and closed with a perforated lid. In the first step, the material was heated up from 25°C to 200°C at a defined heating rate of 10K/min. The temperature was held at 200°C for 10 min and then the sample was cooled down to 25°C at a cooling rate of 10K/min. A second heating run up to 200°C was then started at the same heating rate of 10K/min in order to ensure that a complete cross-linking reaction had been achieved in the first run and that no exothermic peak was visible. The melting point and melting enthalpy were evaluated in accordance with ISO 11257-2 and ISO 11257-3.

Designation	Type	Film thickness [mm]	
		Uncured	Cured
EVA A	Ultra-fast cure	0.46	0.9–1
EVA B	Fast cure	0.45	0.9–1

Table 1. Materials selected for the studies.

Stage of curing	Duration [sec]	Total lamination time [min]
I	300	19.33
II	360	20.33
III	480	22.33
IV	600	24.33
V	720	26.33
VI	1200	34.33

Table 2. Variation of the cross-linking times.

Results and discussion

DMA in shear mode has proved to be a suitable tool for measuring the degree of cross-linking [7–10], as the cross-linking reaction directly affects the thermomechanical properties of the EVA films. In the following discussion the results of the temperature scans and the isothermal characterization will be presented. Furthermore, it will be shown how optimum processing parameters – such as cross-linking time and lamination temperature – can be derived from the results obtained.

"DMA in shear mode has proved to be a suitable tool for measuring the degree of cross-linking."

Thermal behaviour

Fig. 1 shows the differential scanning calorimeter (DSC) thermograms of the

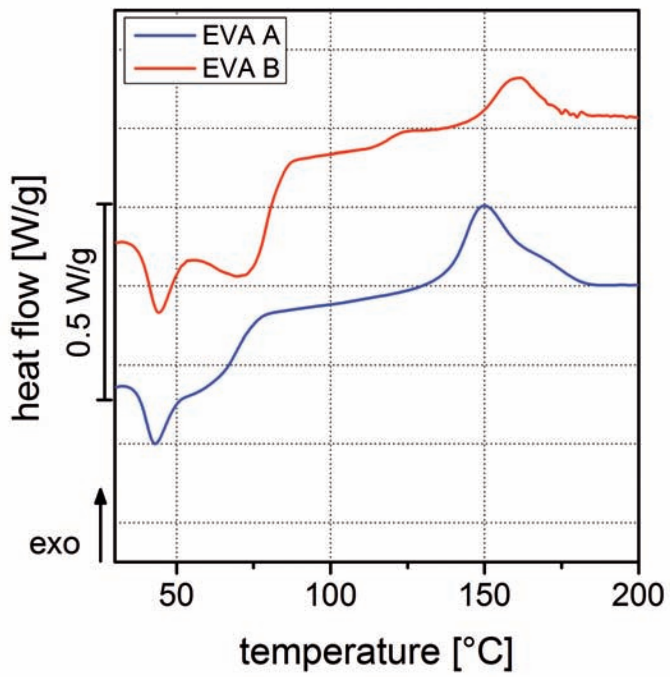


Figure 1. DSC curves of the uncured EVA films.

uncured EVA films. A melting stage can be seen between 30 and 80°C, with a single peak around 45°C and a shoulder between 60°C and 75°C, which is the thermodynamic melting point of EVA.

The peak at 45°C can be attributed to secondary crystallization, which occurs in the area between the primary crystals during slow cooling, storage at ambient temperature or exposure to elevated temperatures [3–5]. An exothermic reaction of the chemical cross-linking reaction due to peroxide decomposition can be observed between 115 and 190°C. Of course, different curing agents were used, which can be deduced from the differences in temperature limits, reaction enthalpy, or shapes of the peaks. A peak temperature of 150°C was measured for EVA A, whereas for EVA B a value of around 159°C was obtained. Furthermore, the two peaks of EVA B indicate a dual curing agent system, with the secondary peak around 125°C and the main reaction peak around 159°C [11].

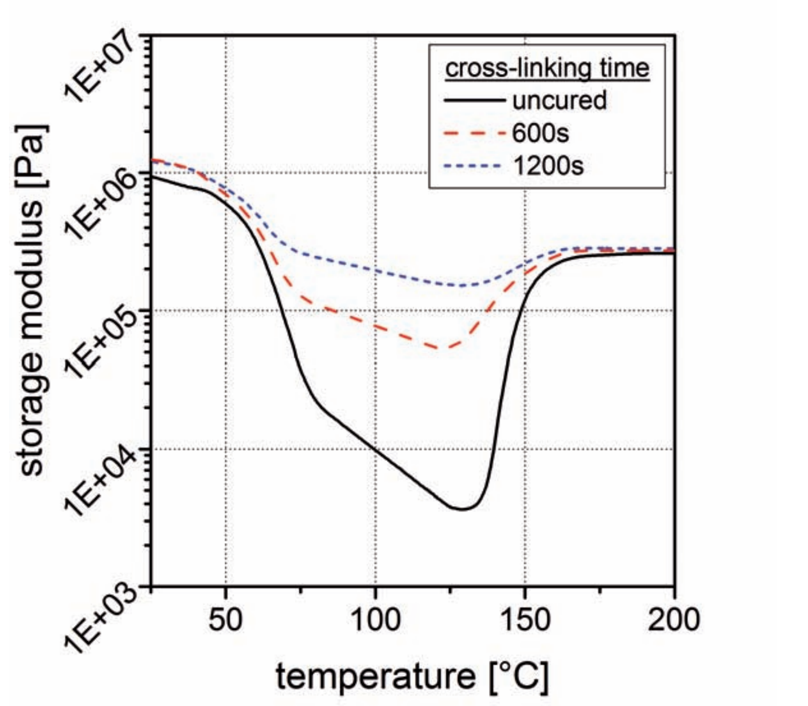


Figure 2. Temperature-dependent storage modulus for uncured and partially cured EVA B film.

Temperature scan

Fig. 2 shows the temperature-dependent shear storage modulus *G′* of the uncured and partially cured EVA B; Fig. 3 shows the temperature-dependent damping factor tan δ. The DMA measurements revealed a clear influence of the lamination time on the modulus and damping factor of the differently cured EVA films. From 60°C up to approximately 75°C, the storage modulus in shear mode (*G′*) drops, where the entire material is in the molten state. At the minimum of the modulus curve, around 125°C, the post-cross-linking reaction is thermally initiated, which is associated with a significant increase in the modulus. This correlates well with the DSC measurements, where the onset of the exothermic cross-linking reaction was found to be around 115°C (see Fig. 1). The increase in storage modulus that follows can be attributed to the formation of a three-dimensional network. After 170°C the modulus levels off, becoming almost independent of temperature, which indicates the end of the cross-linking reaction.

For the differently cross-linked specimens, with increasing cross-linking time there is a smaller reduction in the shear modulus at temperatures above 60°C. The decrease in the modulus G' in the melting region is reciprocally proportional to the lamination time. At temperatures above 60°C, the longer the cross-linking time, the higher the molecular mass and the cross-linking density, and therefore the higher the modulus value.

Regarding the damping factor, however, the opposite behaviour was observed: after the melting region around 60°C, a strong increase in damping factor, which peaked around 125°C, was seen. This can be explained by the higher mobility of the polymer chains in the molten state. At 125°C the cross-linking reaction started and the mobility of the polymer chains was reduced by the increasing cross-linking density. With increased curing time, the damping factor of the partially and fully cross-linked specimen decreased significantly.

"With increased curing time, the damping factor of the partially and fully cross-linked specimen decreased significantly."

For the correlation of thermomechanical properties with gel content, an appropriate indicator from the DMA curve has to be defined. Two possible candidates are the minimum of the shear modulus and the maximum of the damping factor as a function of lamination time. Both indicators show a clear correlation with lamination time and therefore with the actual state of cross-linking. Nevertheless, both indicators exhibit strong scattering between and during the different stages of curing, as these values can be influenced by various external factors, such as the positioning and clamping of the samples, the contact between the shear plates and the specimen, and the uniformity of the specimen preparation. To eliminate these variables, a recently developed self-referencing alternative method for determining the degree of cross-linking from DMA data [7] was applied here. This method involves determining the gradients of the linear sections on either side of the shear modulus minimum, and on the steady-state post-cross-linking section, as shown in Fig. 4. The intersection of these linear extrapolations on either side of the minimum yields the measurement point G'_1, while the intersection of the rising slope and the steady-state section gives the reference modulus G'_2. Taking the modulus ratio G'_2/G'_1 yields highly reliable and reproducible values. A further advantage of this method is that the modulus ratio always converges asymptotically to a value of one for fully cured materials.

Fig. 5 shows the modulus ratio for the EVA films investigated. Different curing behaviour was found for all materials. As expected, the fastest conversion was

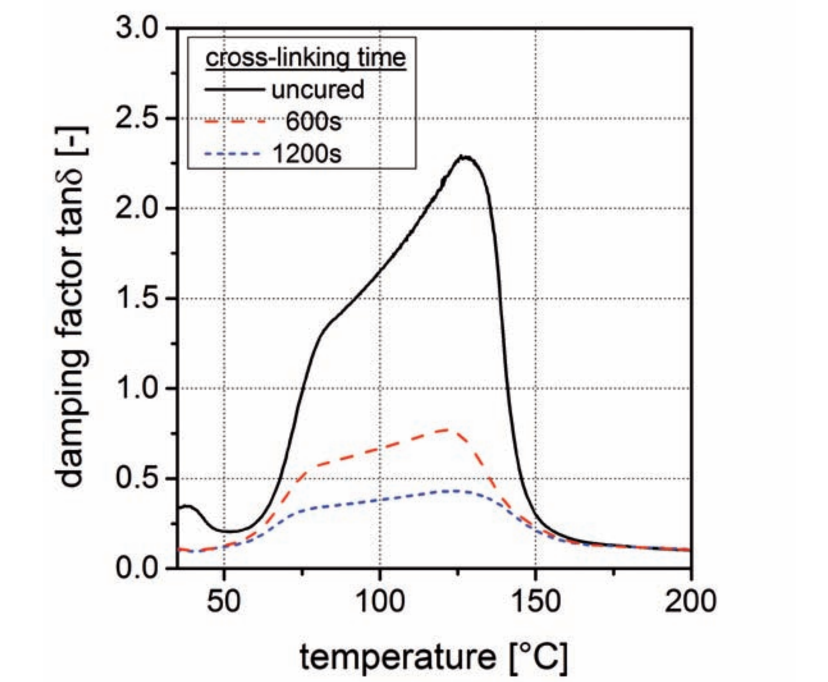


Figure 3. Temperature-dependent damping factor for uncured and partially cured EVA B film.

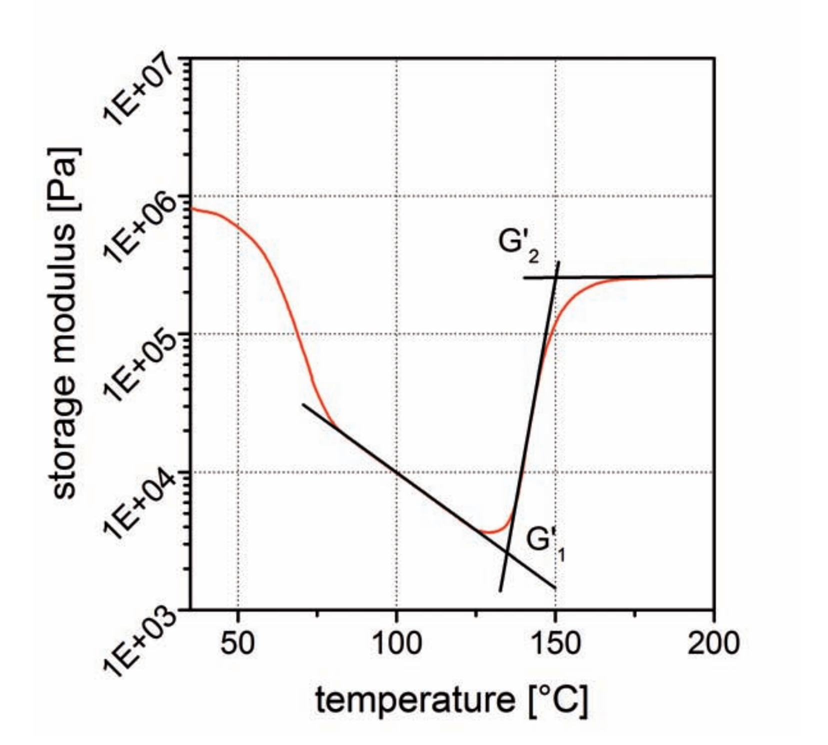


Figure 4. Formation of modulus ratio G'_2/G'_1.

observed for the ultra-fast-type EVA A, already reaching a sufficient state of curing after 360 sec of cross-linking time. The modulus ratio also reveals that a given lamination temperature of 146°C is far too low for a sufficient cross-linking of EVA B: a comparable state of curing was reached only after 1200 sec of cross-linking time. Temperature measurements during PV module laminations have shown that during the first few minutes the temperature of the EVA layer is usually up to 10°C lower than the given lamination temperature. Only by using longer processing times is a complete heating through of the EVA layer achieved. This assumption is supported by the comparison of the modulus ration curves over lamination time. For the ultra-fast-cure EVA A, significant cross-linking was already observed during the evacuation and compression cycle of the lamination process. For EVA B, however, no significant cross-linking could be detected up to 20 min of lamination time. The slight decrease after 20 min of lamination indicates the heating through of the EVA layer by achieving a sufficient temperature for the start of the cross-linking reaction. The temperature was nevertheless insufficient for a fast cross-linking reaction.

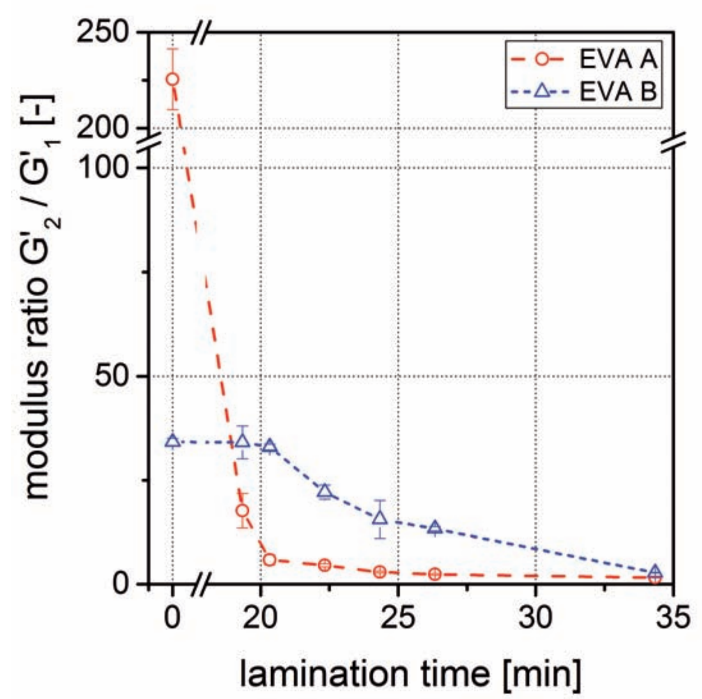


Figure 5. Modulus ratio G'_2/G'_1 as a function of lamination time.

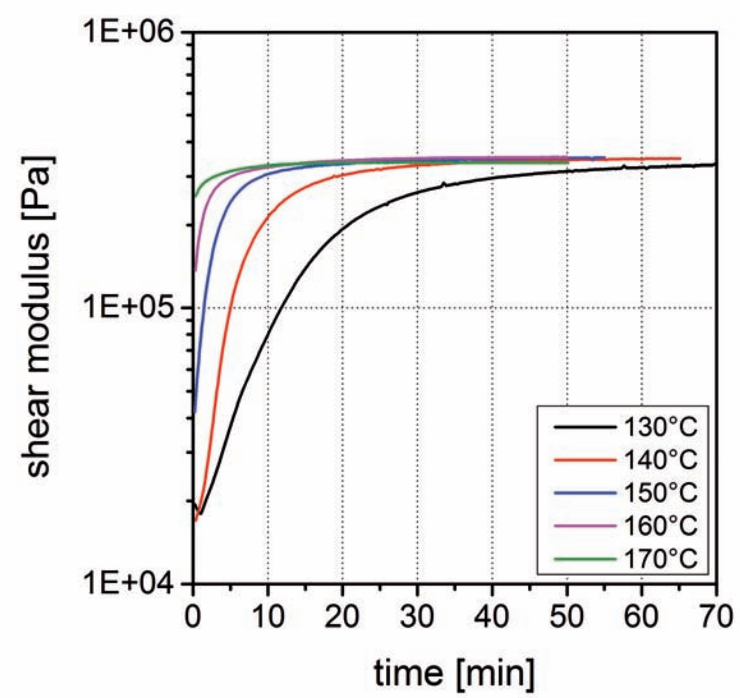


Figure 6. Storage modulus of EVA B as a function of time at constant temperatures between 130 and 170°C.

In a recent study a total of 16 different methods, ranging from classical solvent extraction through different thermoanalytic and mechanical approaches to acoustic and optical spectroscopy, were evaluated in order to investigate the state of cross-linking of EVA [7]. A good correlation between gel content and DMA measurements was found. Moreover, the analytical reliability of the DMA measurements was found to be superior to those of the reference methods, especially for short cross-linking times. From a thermodynamic point of view, a modulus ratio value of less than five indicates a sufficient state of cross-linking, which corresponds to gel-content values between 70 and 80% [7]. Further cross-linking above this state no longer has a significant effect on the thermomechanical properties.

Isothermal scan

In order to optimize the PV module lamination process, not only the final degree of cross-linking but also the kinetics of the curing reaction is of importance. The progress of the curing reaction can be monitored by measuring the thermomechanical properties at various constant temperature levels. The method will be presented next by showing the results of EVA B, which is representative of all the films investigated. Fig. 6 shows the storage modulus of the EVA film under investigation as a function of time at constant temperatures from 130 to 170°C. A significant increase in shear modulus with time was observed. The increase in shear modulus can be attributed to the formation of a three-dimensional network by radical chain reaction. The moment when the shear modulus levels off and becomes almost independent of temperature indicates the end of the cross-linking reaction. Moreover, a significant influence of temperature on the curing reaction can be observed. Whereas at 170°C the shear modulus values reach an almost constant level between 5 and 10 min, at 130°C the shear modulus values are still increasing after 60 min and have not yet reached a plateau. The significant temperature dependence of the curing reaction can be explained by the temperature profile of the exothermic reaction observed with DSC measurements (see Fig. 1)

To further evaluate the reaction kinetics, the shear modulus data have to be scaled and normalized. The scaling of measurement data is also necessary in order to compensate or reduce scattering due to measurement inaccuracies caused by sample preparation and handling. The conversion rate X can be calculated from the shear modulus $G'(t)$ as follows [10]:

$$X = \frac{G'(t) - G'(t_0)}{G'(t_\infty) - G'(t_0)} \qquad (1)$$

where $G'(t_0)$ is the initial shear modulus and $G'(t_\infty)$ is the shear modulus of the fully cross-linked material.

"There is no further acceleration of the cross-linking reaction with temperatures higher than 150°C."

Fig. 7 shows the conversion rates at different temperatures. In general, higher lamination temperatures lead to faster initiation of the cross-linking reaction. Two main conclusions can be drawn from the calculated conversion rates: first, lamination temperatures of at least 140°C are necessary for full conversion to take place in realistic processing times (<900 sec); second, and more importantly, there is no further acceleration of the cross-linking reaction with temperatures higher than 150°C.

This can be seen even more clearly by using an Arrhenius law equation for the description of the cross-linking reaction. The Arrhenius law describes the rate constant k of chemical reactions for a certain temperature T and activation energy E_a:

$$k = Ae^{-E_a/RT} \qquad (2)$$

where A is a pre-exponential factor and R is the universal gas constant. The only variable parameter and driving factor affecting the reaction rate (i.e. decomposition rate of the radical initiator) is the temperature. Fig. 8 shows the Arrhenius plot for the EVA film under investigation for conversion rates of 50, 80 and 90%. Between 130 and 150°C the Arrhenius plot reveals a linear correlation between the logarithmic time and the inverse temperature, with the activation energy as the gradient. A value of 125±7kJ/mol was calculated for the activation energy, which is in agreement with values found in the literature [10]. A further increase in temperature does not lead to an ongoing acceleration of the reaction rate, which can be seen in the more or less constant times for reaching the desired conversion rates at temperatures above 150°C.

This shows that optimum processing times and parameters can be derived using Arrhenius plots. At 150°C, conversion rates of 50, 80 and 90% can be achieved after 200, 330 and 730 sec, respectively, for the investigated material. Note that the lamination temperature on the laminator does not equal

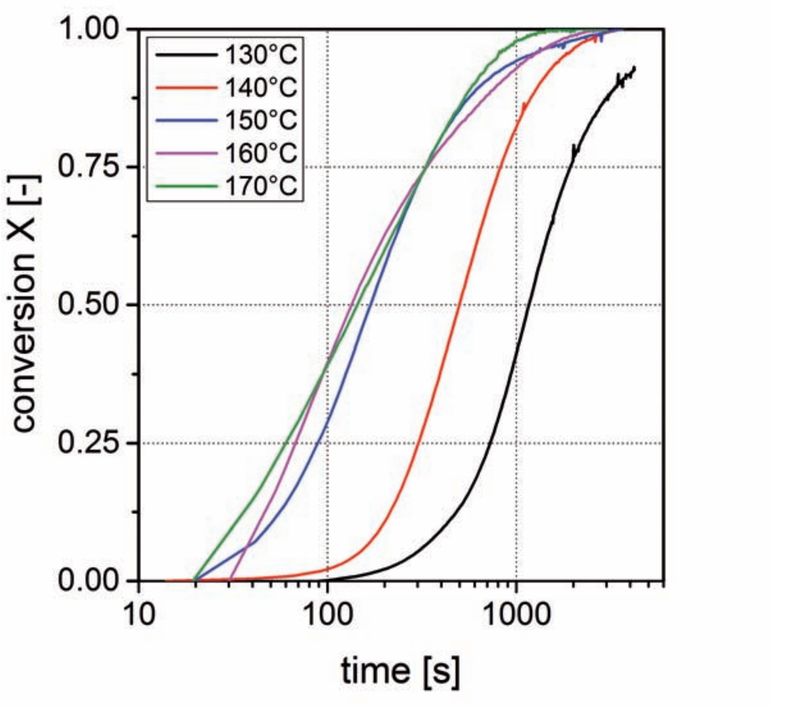


Figure 7. Conversion rate of EVA B as a function of temperature.

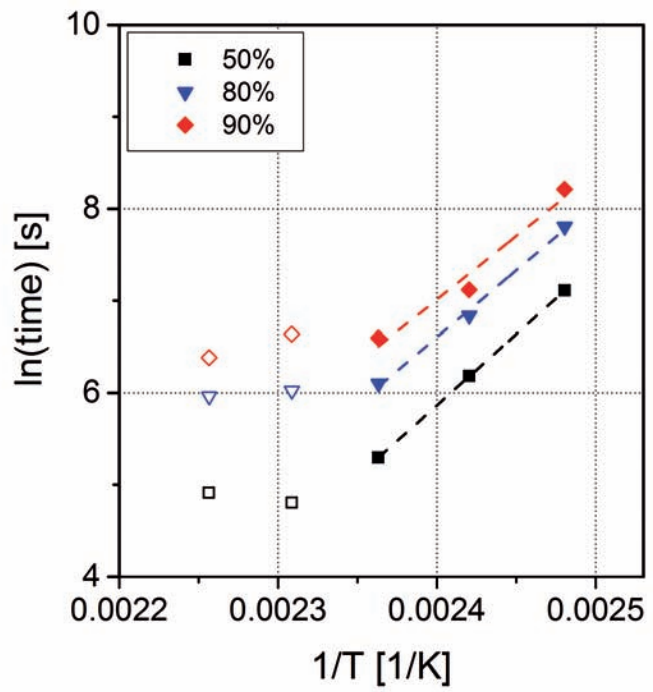


Figure 8. Arrhenius plot of EVA B for conversion rates of 50, 80 and 90%.

PV Modules

the temperature of the EVA layer presented here. Depending on the heating properties of the laminator and the module geometry, a delayed heating of the EVA layer takes place, usually resulting in lower temperatures in the EVA layer than the given lamination temperature.

The main advantage of isotherm scans is that no specific sample preparation is required – the investigations can be done on uncured EVA films. On the basis of the linear relationship between cross-linking time and temperature, and knowledge of the activation energy, a prediction of the progress of the curing reaction at any given temperature is possible. However, phase transitions and decomposition temperatures of polymers or curing agents must not be exceeded, and this must be taken into account. Generally, a prediction of the cross-linking time should only be done within the measured temperature range.

Summary and conclusion

The results presented in this paper demonstrate that DMA is a valuable and reliable characterization method for investigating the curing behaviour of EVA for solar cell encapsulation. DMA in shear mode allows the thermomechanical properties to be continuously measured (even for EVA in the molten state), and therefore the cross-linking reaction to be monitored in situ. The degree of cross-linking can be determined by performing temperature scans on partially cured EVA films. Isothermal scans on uncured samples enable the investigation of curing kinetics of EVA. On the basis of an enhanced knowledge of the cross-linking reaction material, the related process parameter optimization potential of the PV module lamination process can be identified, and optimum processing temperature ranges and minimum cross-linking times can be derived.

> "DMA is a valuable and reliable characterization method for investigating the curing behaviour of EVA for solar cell encapsulation."

Regarding EVA B, temperature scans revealed that the chosen lamination temperature of 146°C was too low for a sufficient state of cross-linking within a reasonable processing time. The assumption was confirmed by DSC measurements, where the main cross-linking reaction peak was found at 159°C, whereas the temperature in the EVA layer during the first few minutes of cross-linking time is usually up to 10°C lower than the given lamination temperature. Only by using longer processing times can a complete heating through of the EVA layer and thus a full conversion be achieved.

Moreover, isothermal scans showed that temperatures greater than 140°C in the EVA layer are necessary for full conversion of the cross-linking reaction. Even more interestingly, further evaluation of the data using the Arrhenius law showed that temperatures above 150°C do not lead to a further acceleration of the cross-linking reaction.

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Multi-busbar technology: Increased module power and higher reliability at lower cost

Sebastian Schindler, Fraunhofer CSP, Halle, & **Michael Volk**, SCHMID Group, Freudenstadt, Germany

ABSTRACT
Recent advances at the cell level and in tabber-stringer equipment have led to the development of the next generation of cell interconnection architecture, resulting in an increase in cell and module performance. The multi-busbar (MBB) concept discussed in this paper delivers the benefits of a saving in material costs, a reduction in total series resistance and an improved light utilization for higher performance at lower cost. The combination of the cell and module concept and the stringer equipment works for a wide variety of cell types and enables an appreciable decrease in cost per watt and module size per watt.

Introduction

There are several clear indications of the effect of changes to the cell interconnection process and overall module architecture. New cell metallization layouts and techniques enable higher efficiencies to be achieved at the cell level, while the latest research in module interconnection schemes – such as half-cut cells – has led to improvements in module power output by decreasing cell-to-module losses [1,2]. Equipment suppliers are offering new process lines to upgrade the state-of-the-art three-busbar cell design with at least four, or even five, busbars.

This paper describes multi-busbar (MBB) technology developed by SCHMID Group as a more refined serial solar interconnection concept. Cell-to-cell interconnection is realized by 15 Cu wires, following the alternating front-side to back-side connection through a stringing and soldering process. The equipment and interconnection process is discussed, complemented by microstructure diagnostics to verify contact formation and reliability.

The proposed technique aims to reduce the amount of silver (Ag) needed for the front cell electrode. With the multi-busbar design, module performance can be increased because of the reduction in the total series resistance of the interconnected cell strings and also because of improved light utilization owing to the round wires.

There are four key advantages to using MBB technology for photovoltaic cells and modules:

1. A reduction in the amount of Ag per cell required for different cell types.

2. Higher cell and module efficiencies because of the new cell metallization layout and multi-busbar stringing design.

3. Adaptable equipment for retrofitting existing module production lines, a reliable stringing process, and conventional string lay-up and module lamination.

4. Improved module reliability and reduced thermomechanically induced stresses and cell breakage.

> "With the multi-busbar design, module performance can be increased because of the reduction in the total series resistance of the interconnected cell strings."

This paper gives a summary of the benefits from a cell perspective, and an overview of the equipment for implementing the multi-busbar interconnection process, as well as the overall module production process. Furthermore, results of micro-mechanical and micro-structural diagnostics of the miniaturized solder joints are presented. The last section focuses on forthcoming work, which will address the mechanical and reliability advantages of multi-busbar interconnection technology.

Cell development and metallization concept

In 2010 Ag usage for photovoltaic applications reached approximately 7% of the annual worldwide supply of this material [3]. At the same time as the usage of Ag has been rising, the price of Ag has been increasing: this poses an important limitation on the growth of solar cell production at lower costs. Thus, a key goal for the photovoltaic industry is to decrease the amount of Ag usage in solar cell production [4].

The multi-busbar design demonstrates a potential for cell and module efficiencies higher than those achievable with the state-of-the-art three-busbar cell design [5]. The multi-busbar design is optimized so that the shaded area and Ag consumption are reduced. The proposed layouts are based on small solder pads and a grid finger scheme, instead of continuous busbars as a soldering pad for the Cu ribbons. New test and measurements set-ups have also been developed [6].

In conventional three-busbar layouts, the length of the fingers between the busbars along with the associated ohmic losses limit the minimum finger width and therefore determine the amount of Ag required to achieve sufficient fill factors. With the reduced finger lengths of the multi-busbar design it is possible to tap the full potential of modern metallization techniques, such as fine-line screen printing or inkjet seed-layer printing combined with light-induced plating. The obvious benefits are a high fill factor with significantly reduced Ag consumption and less shading of the active area [7].

Two different processes are used for the metallization of the solar cell: 1) fine-line screen printing, and 2) seed-layer and plating techniques of the front electrodes [8]. Table 1 compares the amount of Ag required for the multi-busbar layout with that for a three-busbar layout. With improved alignment and fine-line and dual printing, the screen-printing process has gradually been improved and the printing paste consumption reduced

	Group 1 (MBB layout)	Group 2 (MBB layout)	Group 3 / Reference (three-busbar layout)
Screen printing	30–33mg finger paste		
	30–32mg pad paste		
Seed layer		8–9mg	11–12mg
Base layer		20–25mg	85–90mg
Total	60–65mg	28–34mg	96–102mg

Table 1. Total amount of Ag consumption for the different types of front-side metallization, according to Braun et al. [8].

over the years: a reduction of 40% has been realized. For the other approach of seed-layer inkjet printing and Ag plating, only one third the amount of Ag is needed. The results have confirmed the formation of a sufficient front electrode on the solar cells, leading to an even greater reduction in Ag.

The overall metallization design on the front side is very flexible. The metallization pattern is highly adaptable to specific customer layouts, process requirements (pad size vs. alignment, etc.) and optimized cell efficiencies. Figs. 1 and 2 show two different metallization layouts: seed-layer inkjet printing and plating, for which a standard busbar-less small meshed layout was chosen; and screen-printed contacts, for which an improved design, with a further reduction in the number of pads, has been developed.

The results showed that the amount of Ag can be drastically reduced; moreover, the multi-busbar concept measures up to the proposed long-term goals in international roadmaps: the 'International technology roadmap for photovoltaic' (ITRVP) [4] indicates a target of 50mg of Ag per cell in 2020.

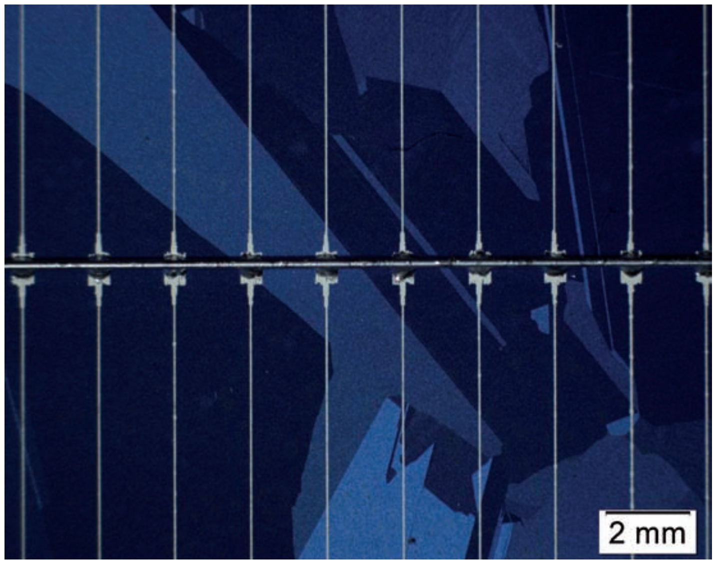

Figure 1. Ag-plated contacts: standard busbar-less design, with soldering pads on the grid fingers.

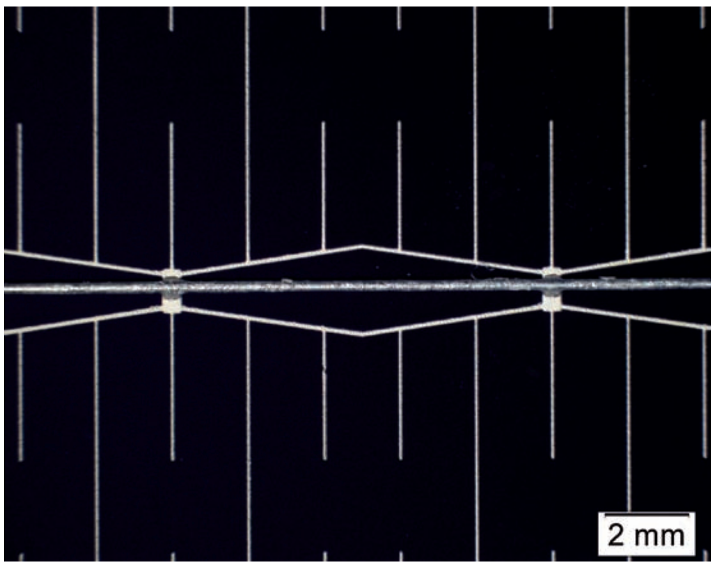

Figure 2. Ag screen-printed contacts: improved design, with a reduced number of solder pads and a more complex grid finger layout.

Cell stringing process and multi-busbar connector

A multiple busbar concept with small Cu wires for cell interconnection was first proposed by the Canadian company Day4Energy [9]; this technology is now promoted by Meyer Burger under the name of 'smart wire connection' [10]. The smart wire approach combines the stringing and lamination process into one step, bonding indium-coated wires to the solar cells.

In comparison, the multi-busbar connector discussed in this paper is similar to a classical stringer step followed by a standard lamination process: the solar cells are still interconnected in an alternating way, from the front side of one cell to the back side of the adjoining cell. The cells are mechanically and electrically interconnected by 15 Cu wires, and assembled into conventional cells strings; they are then picked and placed for further module assembly (cross interconnection and encapsulant lamination). This has the advantage that the overall advances in technology can be implemented in existing production lines: the equipment can integrated, with only the need to replace tabber-stringer equipment.

"Advances in technology can be implemented in existing production lines."

With the multi-busbar development at the cell level, a new generation of process equipment [11] for the cell-to-cell interconnection was necessary in order to meet the requirements for connecting small Cu wires on busbar-less cells. Since the alignment of the cells and the wires is crucial, the multi-busbar stringer uses high-precision image processing to determine the position of the metallization pattern. The string assembly is carried out on preheated vacuum chucks via IR soldering (see Fig. 3). All 15 tin-coated Cu wires are soldered to the front and back sides of the cell in one step, as shown in Fig. 4. To enable easy assembly of the module matrix, the 15 wires at both ends of the strings are automatically interconnected by an end ribbon. Fig. 5 shows an SEM image of Cu wires with the pointwise solder joints on the multi-busbar cell metallization pattern.

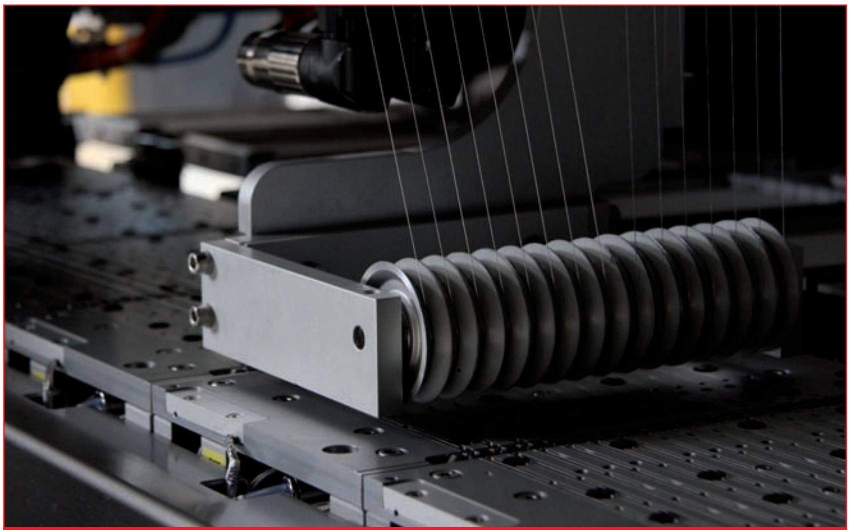

Figure 3. Multi-busbar connector: vacuum chuck used to align the 15 Cu wires on the solar cell.

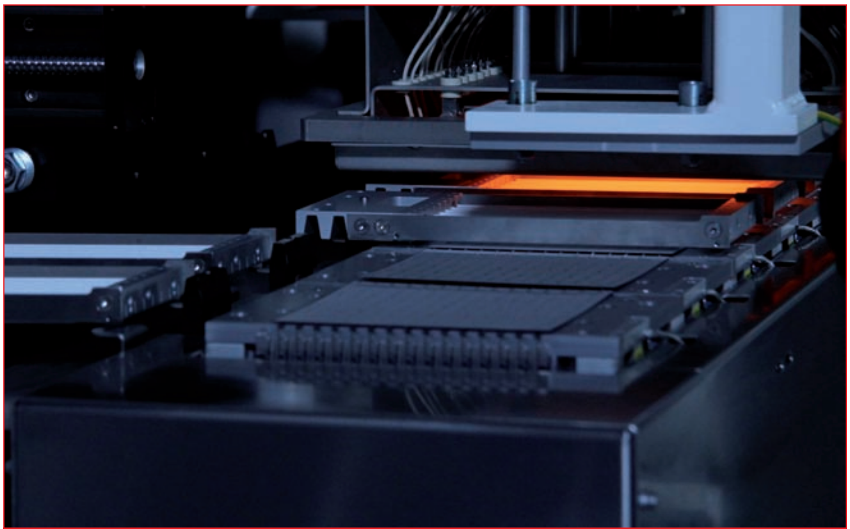

Figure 4. Multi-busbar connector: cell vacuum chucks and the IR soldering unit for the soldering process.

PV module assembly process

As already mentioned, the overall module assembly process follows a state-of-the-art workflow. The metallization process, the cell inspection and measurement, and the tabber-stringer process equipment are subject to change, but the subsequent string cross-connection to the junction box and the module lamination are standard.

Fig. 6 shows the process flow of the multi-busbar module manufacturing concept, with the changed processes marked on the flow chart. No additional steps are necessary to realize the multi-busbar cell/module concept, compared with current conventional PV cell and module assembly processes. At the cell fabrication level, only the metallization process is modified: a screen-printing process is still used, but new screen masks are necessary. For quality control and inspection, a new contacting unit is required because of the modified front-side layout of the multi-busbar cell.

For module production, only new stringing equipment has to be installed, so production can be easily ramped up. In the lay-up process the cell strings are placed onto the glass. A minor adaptation of the cell string interconnection needs to be performed to cross-link the 15 multi-busbar Cu wires.

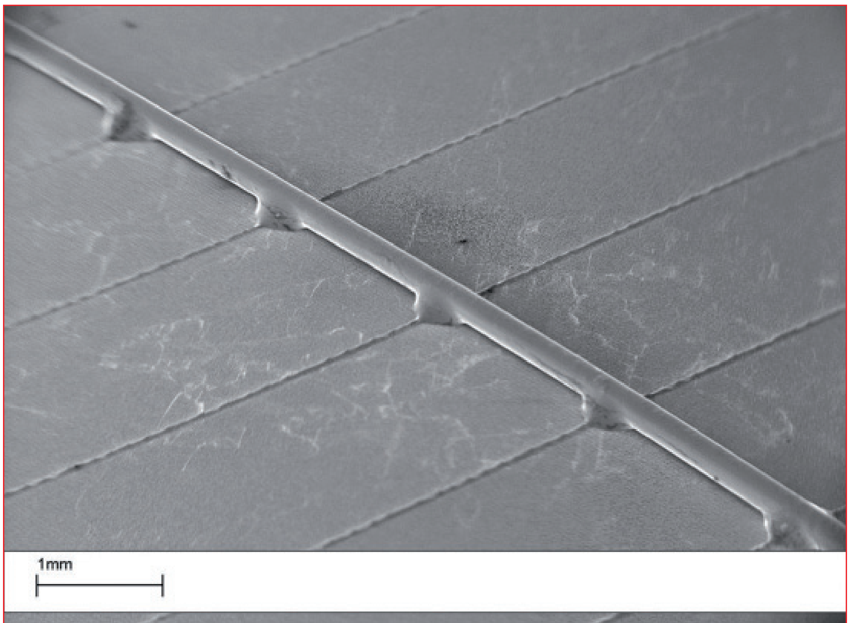

Figure 5. SEM image of Cu wires soldered to the multi-busbar cell metallization pattern.

Contact formation and evaluation of solder joints

Besides the benefits at the cell level, extensive studies relating to contact formation, process and material interactions, and reliability assessment have been carried out to optimize and validate the module concept. In a recent work by Schindler et al. [12], the contact formation of the soldering process was investigated for the MBB cell metallization design. Different technological approaches, such as varying the Cu wire diameter or the cell metallization, were evaluated by means of micro-mechanical pull tests.

By drawing upon expertise in microelectronics and microsystems technology for failure diagnostics, as well as a material evaluation of adhesion technologies and system integration (e.g. wire bond contacts or welded contacts), a universal tool (see Fig. 7) was co-developed [13] to characterize the solder contact strength of solar cell interconnections (both standard H-pattern cell layouts and new cell metallization concepts and layouts). This mechanical testing of the MBB solder joints was evaluated by a pull test of the miniaturized solder joints, as this is a suitable way of testing the influence of process parameters and material mixtures for interconnections. Force measurements of the pads were conducted on the solar cell front-side metallizations (see Fig. 8). The single-point pull-force interconnection values for the sequences were assigned maximum values, and the mean value and standard deviation for the measured specimen were calculated. In addition, the fracture mode after the pull test was recorded in order to seek a possible correlation between the force values and the mechanically induced contact deterioration within the test regime.

The measurements indicated good force values for these miniaturized contacts. The results also showed that the metallization process plays an important role in mechanical strength during pull tests of the solder joints.

"The results showed that the metallization process plays an important role in mechanical strength during pull tests of the solder joints."

The solder joints on inkjet seed-layer printed and Ag-plated pad structures resulted in lower pull force values than when screen-printed Ag metallization was used. For the screen-printed contact pads, the pull forces are above 1N, with values over 2.5N being measured for several contacts (Fig. 9). The solder joints using the inkjet seed-layer printing and Ag-plating technology resulted in a pull force mean value of around 1N in the mechanical tests.

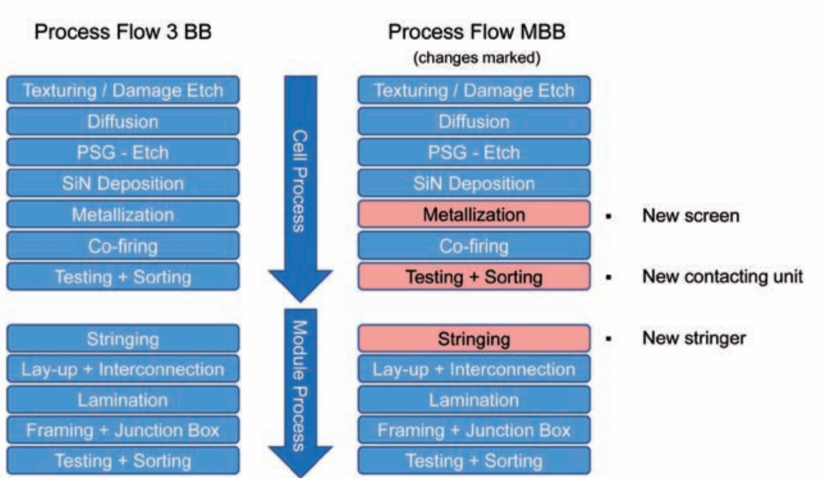

Figure 6. Process flow of multi-busbar cell manufacturing and module assembly steps.

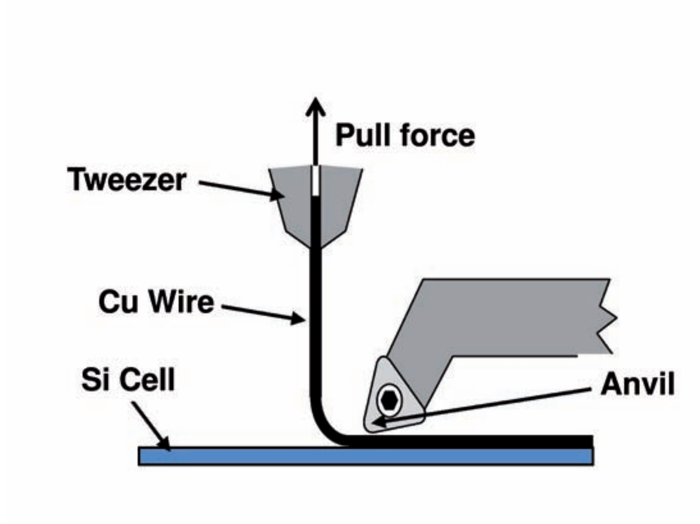

Figure 7. Test set-up for the mechanical pull tests.

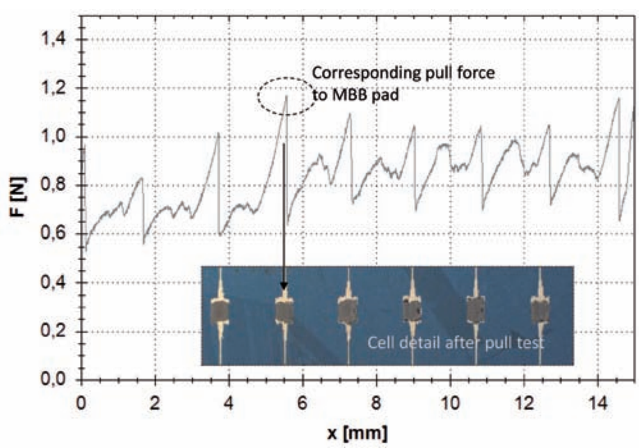

Figure 8. Typical force-pad sequence of the contact force measurements, showing that the wire had been soldered to every single pad.

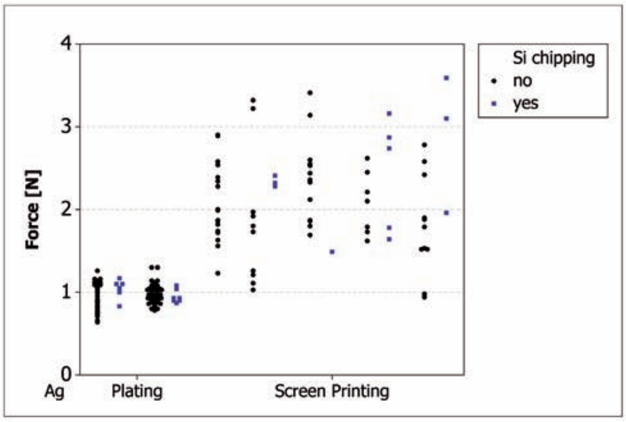

Figure 9. Force values of the single solder pads for the two metallization types, with documented Si chipping.

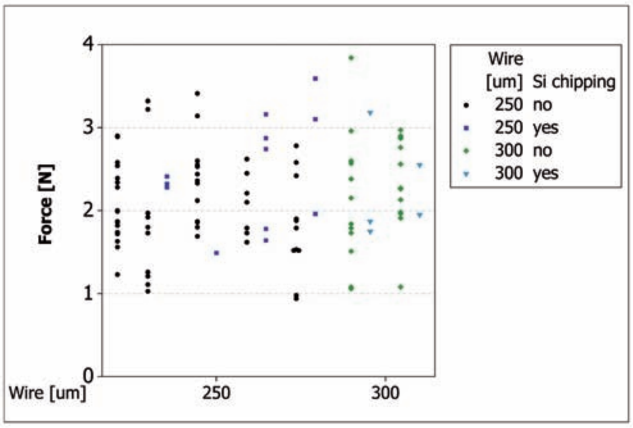

Figure 10. Force values of the single solder pads for two wire diameters, with documented Si chipping.

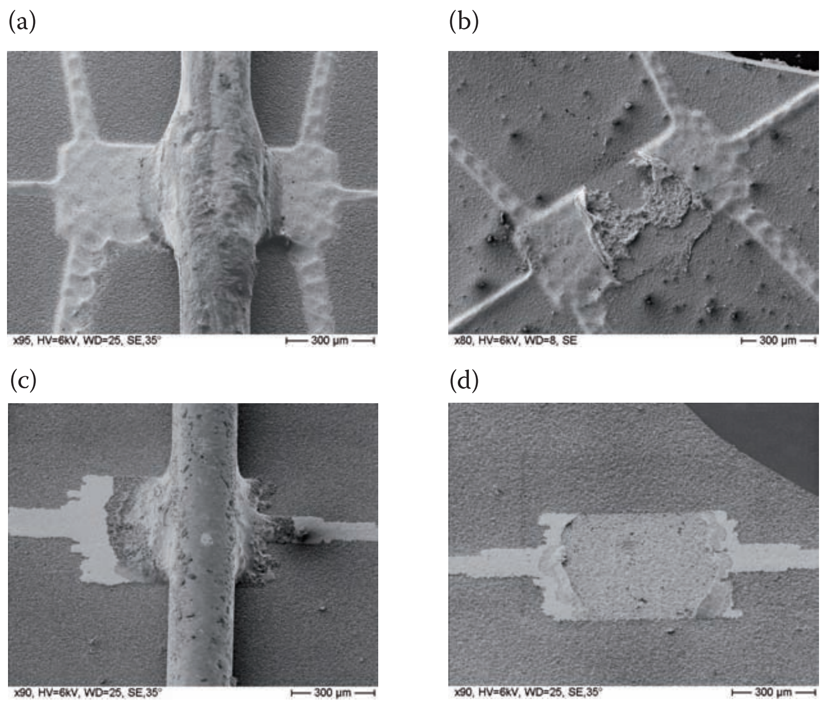

Figure 11. SEM images of soldered Cu wires in cell metallization pads, and their main fracture mode after the pull test: (a-b) screen printing; (c-d) Ag plating.

To compare the peel force values of multi-busbar solder joints and standard ribbons, the width of the soldered area has to be taken into account. The contact area width of about 600µm is 40% of the width of a typical three-busbar ribbon (1.5mm).

No significant difference in quality of the soldered contacts could be observed when the Cu wire diameter was varied (Fig. 10): similar results for wires of two different diameters were obtained when soldered with the production equipment.

A detailed analysis of the contact fracture modes after the pull test revealed considerable differences in the two types of metallization (Fig. 11). Wire diameter variation did not have a significant influence on the fracture mode after the pull test.

The screen-printed solder pads exhibited significant residues of the metallization and side-wall solder residues of the solder meniscus. The inkjet seed-layer printing and Ag-plated pad structure was completely separated from the cell after the test, and the cell surface structure was visible. Partial Si chipping within the soldered area on the specimen was noted. This conchoidal fracture mode was observed for both metallization types (see Fig. 12), but could not be correlated with specific force values.

The contact formation of the solder joints was analyzed by means of microstructural diagnostics. The SEM images (Fig. 13) verified that the soldering results of the tabber-stringer equipment were homogeneous. The tin coating of the Cu wires always wetted on the metallization pad area, and a uniform meniscus from the Cu wire to the solder pad was visible.

The metallographic cross sections in Fig. 14 show in detail the solder meniscus of the solder joints. The solder meniscus solidified to a uniform shape from the Cu wire to the pad area, and no dewetting or dissolution of the Ag metallization could be detected. The solder joint volumes are significantly larger than for conventional interconnected solder joints with tin-coated Cu ribbons; from the stress relaxation and material science point of view, this feature is assumed to be of additional benefit to contact reliability, and therefore to overall module performance and reliability.

Conclusions and further work

The new metallization layout has proven benefits of higher cell efficiencies, invariably associated with a reduction in the amount of Ag needed for the front cell electrode.

Two technical approaches – fine-line screen printing, and seed-layer inkjet and light-induced plating – enable new cell metallization layouts with significantly reduced finger widths and cross sections.

> "The new metallization layout has proven benefits of higher cell efficiencies."

The pointwise stringing process produced reliable soldered contacts for both cell metallization and wire types. Further investigations will be carried out to verify the overall machine set-up with regard to robust and repeatable soldering parameters.

Micro-mechanical testing of the solder joints was carried out by means of a pull test, which is a suitable method for testing the mechanical solder joint strength of the contacts. The pull test measurements, especially for screen-printed MBB structures, yielded good pull forces for the miniaturized solder contacts [14,15]: the values were comparable to (or better than) the results for three busbars on a per width basis. The metallization process plays an important role in the mechanical strength of the solder joints during pull tests. The solder joints with Ag-plated pad structures exhibited lower pull forces than with screen-printed Ag metallization. For the screen-printed contact pads, the pull forces were greater than 1N, and values over 2.5N were even obtained for several contacts. Solder joints with the inkjet seed-layer printing and light-induced Ag-plating technology yielded a mean value of around 1N in the mechanical tests. All contact configurations demonstrated very good wetting of the solder from the Cu wire to the pad area. The multi-busbar connector equipment produced a uniform solder meniscus on the pad areas. The measured pull forces do not depend on the diameter of the Cu wires (250µm vs. 300µm), but optimization of the wire diameter, for either reduced shading or lower series resistance, is possible.

The determination of the minimum pull force which is still compatible with module reliability will be the subject of further investigations. Clearly, different metallization technologies might show

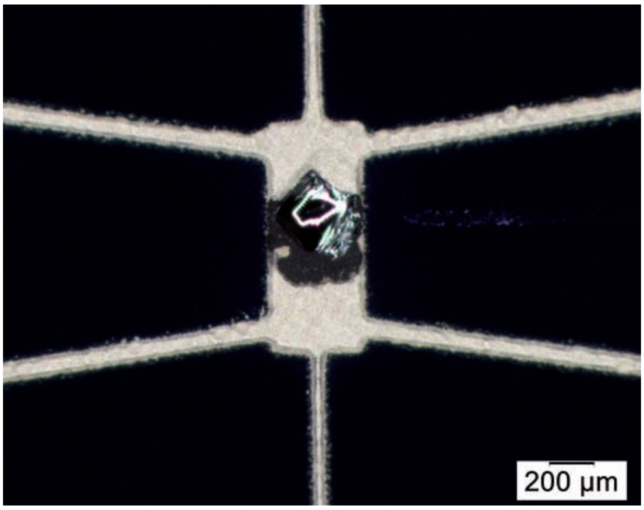

Figure 12. Detailed microscopy image of the fracture mode after the pull test, with conchoidal fracturing of silicon within the pad area.

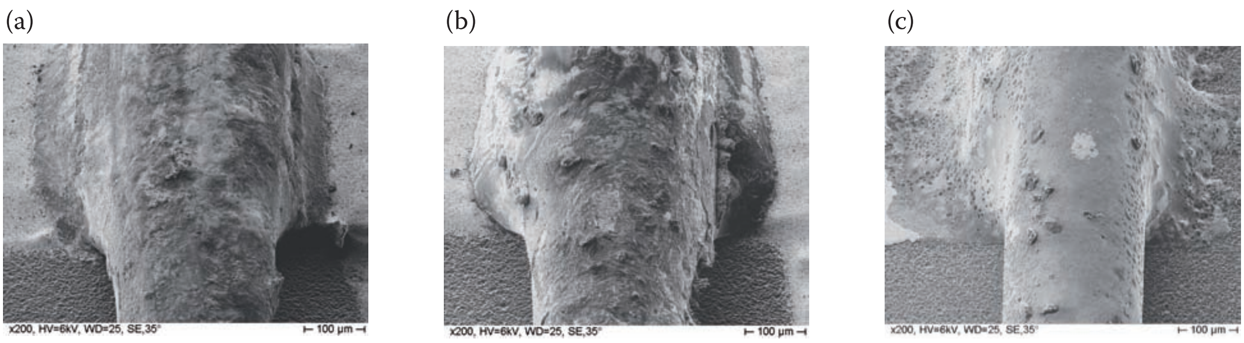

Figure 13. SEM images of soldered Cu wire in cell metallization pads: (a) screen printing, 250µm Cu wire; (b) screen printing, 300µm Cu wire; (c) Ag plating, 250µm Cu wire.

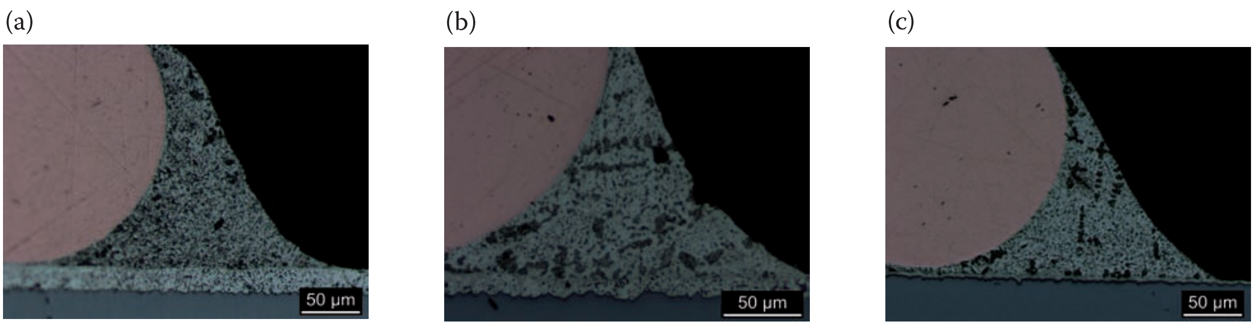

Figure 14. Cross sections of soldered Cu wire in cell metallization pads, and their main fracture mode after the pull test: (a) screen printing, 250µm Cu wire; (b) screen printing, 300µm Cu wire; (c) Ag plating, 250µm Cu wire.

different minimum pull forces.

Further investigations of the influence of cell breakage and induced stresses on the soldering are in progress. A combination of in situ electroluminescence (EL) measurements and four-point bending apparatus is therefore proposed for evaluating the contributing factors of cell breakage due to process parameters, module layout and combinations of materials used [16].

It is assumed that multi-busbar metallization structures will reduce mechanically induced stresses within the cell: the probability of cell breakage will therefore be reduced. The mechanical stress on the solder joint will increase, but, because of the benefits of significantly larger solder volumes, the potential for relaxation and stress restraint is increased. Further investigations are ongoing and will be the subject of forthcoming publications to prove the benefits and reliability of the multi-busbar module technology.

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PV Modules

Certification of solar glass for PV application

Stefan Brunold, **Florian Ruesch** & **Lukas Omlin**, Institute for Solar Technology SPF, Rapperswil, Switzerland

ABSTRACT
The SPF solar glass certification was developed in 2002 to guarantee the quality of glazing for use as a transparent cover for solar thermal collectors. More than 200 glass types from leading manufacturers have been measured and certified to date. Despite the certification having been explicitly developed for solar thermal applications, it became widely used in the PV module industry, even though the results are not transferable and may lead to erroneous conclusions in some cases. In 2012 the certification was therefore adapted to the needs of the PV industry, and a dedicated PV solar glass certification has since been available. This paper explains the fundamentals of the certification process, which consists of three performance characterizations: 1) transmissivity, 2) incident angle modifier (IAM), and 3) UV degradation. Results are discussed for different representative glass types, including float glass, anti-reflective-coated glass and rolled glass with different structures. Furthermore, the performance of these glass types when used as covers of crystalline silicon PV modules is compared. The examples presented also highlight the advantages of the adapted characterization methods compared with standard glass measurements.

Introduction

The performance of a PV module depends on, among other things, the optical properties of the glass used for the cover. Recent developments – such as anti-reflective (AR) coatings or heavily structured glasses – directly address the optical performance of the glass cover in order to increase the module efficiency and decrease the relative cost of solar electricity. Assessing and quantifying the effect that the glass cover has on the yield of an entire module is a laborious task. Nevertheless, because cost pressure on manufacturers has increased in recent years, this information is very important in accurately determining estimates relating performance to price.

The Institute for Solar Technology (SPF) has a long tradition in testing and certification of different materials and systems for the solar industry. In 2002 SPF introduced a certification for solar glass used in solar thermal applications in which the glass is the front cover of a solar thermal collector. Since then, more than 200 glasses from leading glass manufacturers have been certified. Because of the lack of any other certification for solar glass it also became widely used in the PV industry. The certificates and corresponding test results are published on the internet (www.spf.ch). As this certification scheme was specially tailored to solar thermal applications, its results can lead to misinterpretations when directly transferred to PV applications.

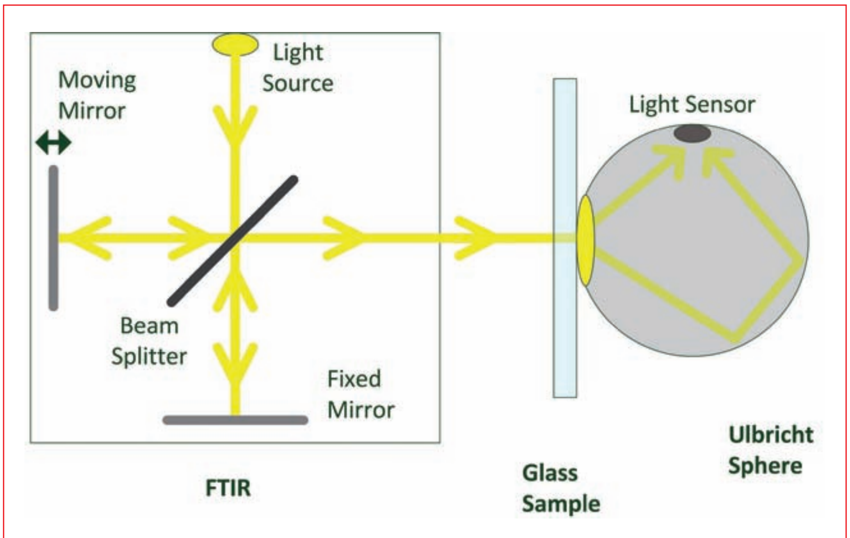

Figure 1. Measurement of direct/hemispherical transmittance using an integrating sphere. The diagram shows a Fourier transform spectrometer (FTIR), but other types of spectrometer can also be combined with integrating spheres.

> "A new certification procedure adapted specifically to the application of glass as the cover sheet for a module with crystalline silicon cells was introduced by SPF in 2012."

The characterization process was adjusted during a project funded by the Swiss Federal Office of Energy, and a new certification procedure adapted specifically to the application of glass as the cover sheet for a module with crystalline silicon cells was introduced by SPF in 2012. The result of the certification is the so-called *glass efficiency factor*, which is intended to be directly proportional to the influence that the glass has on the performance of a typical PV plant in central Europe. The certificate takes into account only the optical properties of a particular glass.

Fundamentals of optical glass measurement

The common method of assessing the performance of solar glass is to measure the direct/hemispherical spectral transmittance; for such measurements, spectrometers combined with integrating spheres (Ulbricht spheres) are used. Fig. 1 shows an example of such a set-up, in which the measured glass is situated in an air environment. The SPF optical laboratory set-up, with an integrating sphere and a sample glass in front, is shown in Fig. 2.

For PV applications a weighted integration of the transmittance spectrum by a typical solar spectrum and a typical sensitivity of the desired cell technology can provide a single value of the 'overall transmittance', and is referred to as the transmissivity. Conventional untreated solar glass achieves a weighted transmittance in the region of 91%, with around 4% being reflected at the front side and around 4% at the back because of the difference in the refraction index of glass ($n_{glass} \approx 1.5$) and air ($n_{air} \approx 1$) (see Fig. 3). For good solar glass, less than 1% is lost by extinction in the glass body. Multiple reflections also take place internally but only account for about 0.2% of the total transmitted light.

Because of the direct lamination of silicon cells to the back side of the glass, the optical situation for a typical PV module is different from that in the usual air–glass–air set-up, as can be seen in Fig. 4. The matching of the refractive indices of glass and the embedding material (mainly EVA) almost eradicates the reflection at the back side of the glass: for typical values ($n_{glass} = 1.5$; $n_{EVA} = 1.48$) the reflection is less than 0.005% and can be neglected. Despite a glass transmissivity of only 91%, measured using standard techniques, around 95% of the incident light reaches the cell in a typical PV module setting. This value can be increased to more than 98% by the use of AR coatings.

The new certification scheme, which will be explained in the next section, introduces a method for correcting the transmittance measurement for the back-side interface reflection and quantifies the amount of light transmitted to the cell. In a typical cell there are also reflections from the cell, wiring and backsheet, which are to some extent reflected back to the cell at the glass front surface. Since this effect is strongly dependent on the cell and wiring type, it is not taken into account in the certification process. For typical modules (7% reflection, flat untreated glass), the magnitude of the effect is of the order of 0.3%, and this is now decreasing as a result of ongoing cell improvements or the use of AR coatings.

The above-described inconsistency between the usual measurement method and a typical module setting also exists in the assessment of the angle-dependent transmittance, usually characterized by the incident angle modifier (IAM). The next section also describes a new method for the assessment of the IAM in a typical module setting, without the glass–air back-side interface.

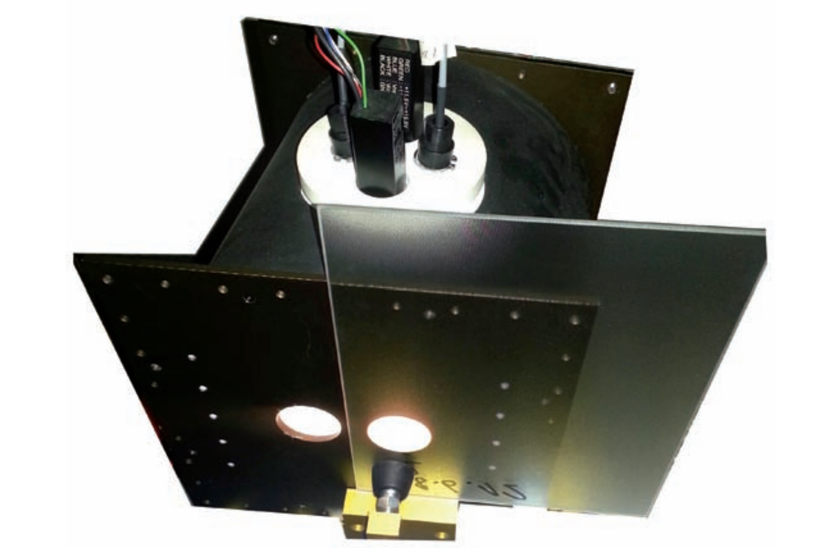

Figure 2. Sample glass in front of an integrating sphere at the SPF optical laboratory – the sphere is inside the black housing. During measurements, the sample glass covers one of the two sphere apertures. Four detectors with different wavelength sensitivities are fixed on the top of the sphere.

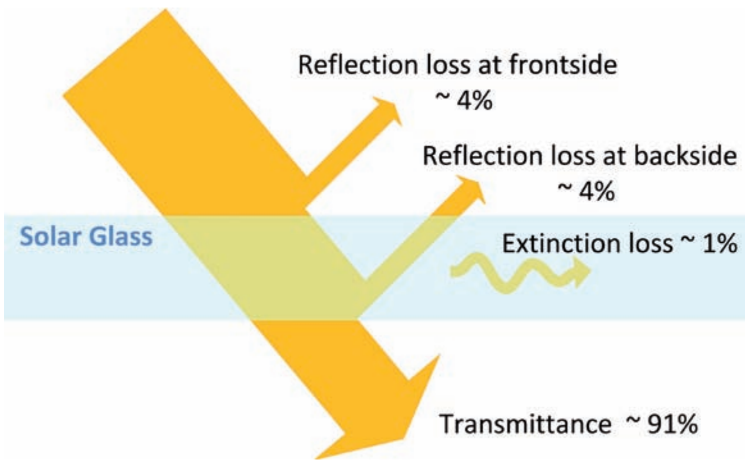

Figure 3. Optical losses of solar glass in an air–glass–air set-up.

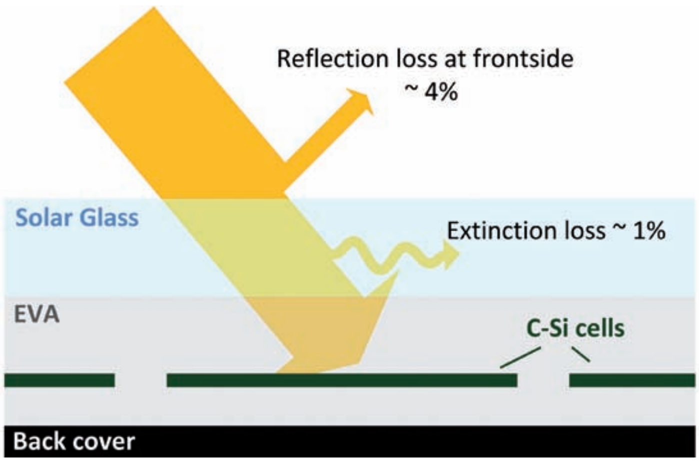

Figure 4. Simplified model of the optical losses caused by the glass in a PV module set-up.

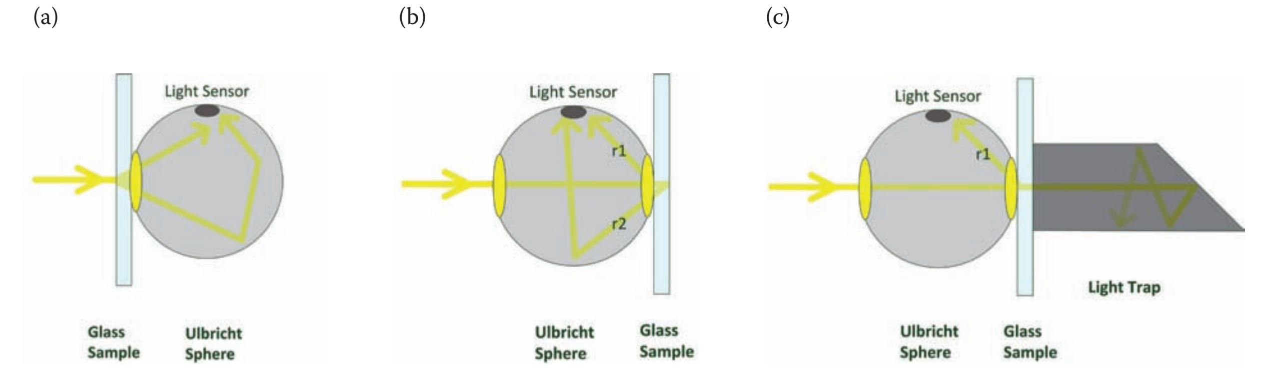

Figure 5. Calculation of the BIC transmittance from three measurements: (a) transmittance measurement in air; (b) reflectance measurement in air; (c) reflectance measurement with a light trap.

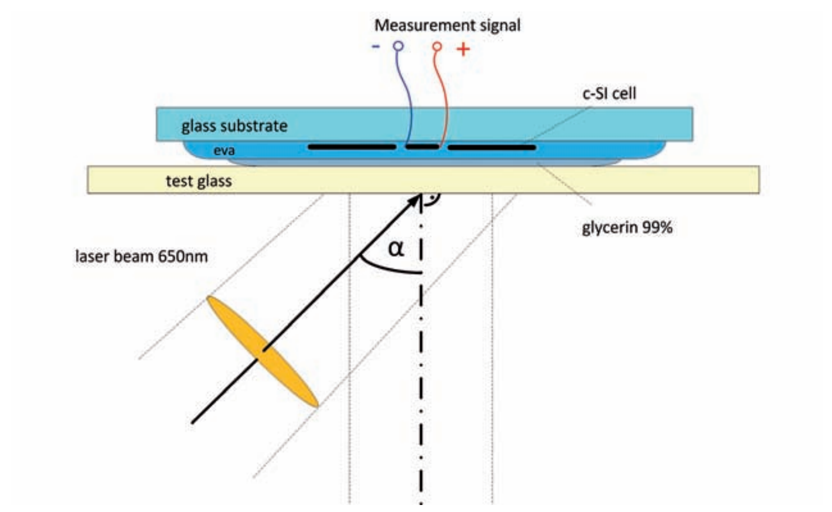

Figure 6. Schematic of the equipment for measuring the IAM of a sample glass. To eliminate the reflection from the back side, the glass is optically coupled to the detector using liquid glycerin.

Glass certification scheme for PV application

The aim of condensing all assessed optical performance characteristics of a solar glass into a single value has led to the definition of the PV glass efficiency factor $\eta_{GL,PV}$:

$$\eta_{GL,PV} = F_{\tau,PV} \cdot F_{IAM,PV} \cdot F_{UV,PV} \quad (1)$$

This quantity is the product of three performance factors (assessed using different methods): the transmittance factor ($F_{\tau,PV}$), the incident angle modifier factor ($F_{IAM,PV}$) and the ultraviolet (UV) degradation factor ($F_{UV,PV}$). These three factors will be explained in the following sections. The idea of these performance factors is to express the influence of a performance characteristic by a single number, which is proportional to the influence of the glass on the annual performance of a defined reference system. This system consists of crystalline silicon PV modules located at Rapperswil in Switzerland (typical central-European climate, coordinates: longitude = 8.82° E, latitude = 47.23° N), with an inclination angle of 30 degrees and facing south. It has been shown in the literature that the results are not very sensitive to changes in the reference system and, with good agreement, the results are transferable to other locations [1].

Transmittance factor $F_{\tau,PV}$

The most important performance characteristic of a glass cover sheet is its transmissivity, which is mainly influenced by the content and oxidation state of iron ions and by the quality of an AR coating. As mentioned in the introduction, the transmittance in an air–glass–air setting is different from that in a PV module, so for this reason the 'back-side interface corrected (BIC) transmittance' has been defined. This consists of the fraction of incident light passing the glass in a module setting, when a perfect match of glass and encapsulation material is assumed.

> "The most important performance characteristic of a glass cover sheet is its transmissivity."

The BIC transmittance cannot be measured directly, but is calculated from three different measurements: 1) common total transmittance measurement in air; 2) total reflectance measurement in air; and 3) reflectance measurement where the reflection at the back side of the glass is eliminated by a light trap (Fig. 5). A more detailed description of the model for the assessment is given in Omlin, Ruesch & Brunold [2], where multiple reflections within the glass are also taken into account. The transmittance factor is calculated by a weighting of the BIC transmittance spectrum by a typical solar spectrum AM 1.5 [3] and by the sensitivity of crystalline solar cells [4].

Incident angle modifier factor $F_{IAM,PV}$

For the performance of a solar plant, it is not only the module's efficiency for direct normal incident light that is important, but also its performance for light hitting at several acute incidence angles. The IAM describes the change in performance for different incidence angles relative to normal incidence angles. In the case of a PV module, the IAM mainly depends on the glass front side (refractive index, coating and structure).

A measurement set-up has been developed to determine the IAM (at angles of 30, 40, 50, 60 and 70 degrees relative to normal incidence) of a sample glass in a PV module setting (Fig. 6), which consists of a c-Si measurement cell (from a leading manufacturer) that has been encapsulated in EVA, where only a small area (20mm × 20mm) in the centre of the cell is active and electrically isolated from the rest. The sample glass can be optically coupled to the test cell using liquid glycerin with a refractive index matched to the EVA used. The cell is illuminated from different angles by a homogeneous collimated laser beam over an area that is much larger than the active area in order to counteract border effects. It was demonstrated that this monochromatic light of 650nm was representative of the entire spectral range encountered in practice [1].

To eliminate the effects of the cell used, the measurement of a sample glass is always compared with a reference measurement of the complete set-up without a coupled glass. Weighting factors are introduced in order to quantify the influence of a measured glass IAM to the reference solar plant (Rapperswil, Switzerland, 30-degree inclination, south orientated) and condense all measured angles into one single value – the incident angle modifier factor $F_{IAM,PV}$. Values of the weighting factors and the formula for the calculation are given in Omlin, Ruesch & Brunold [2]; the derivation of the factors and a sensitivity analysis are given in Ruesch, Omlin & Brunold [1].

UV degradation factor $F_{UV,PV}$

UV radiation can change the oxidation state of metal ions in the glass bulk or can affect the AR coating. Both effects have a direct influence on the transmittance of a solar glass, so for that reason an accelerated UV degradation test was introduced. A sample glass is exposed for 250 hours to a dose of 80kWh/m^2 of UVA and 3kWh/m^2 of UVB, which corresponds to an annual load in central Europe. After this UV exposure, the change in performance is measured and condensed into a single factor – the UV degradation factor $F_{UV,PV}$. Full details of the calculation of this factor are given in Omlin, Ruesch & Brunold [2].

Certification

A classification system was introduced in order to increase the comprehensiveness of the certificate for end users. Solar glasses are split into two groups: group P (Table 1), for untreated glass; and group R (Table 2), for single-sided AR-treated glass. A finely graded sub-classification of these groups is also made, depending on the glass efficiency factor. If the glass does not achieve a specific value, it is no longer classified as solar glass. All certified glasses are published on the SPF website (www.spf.ch).

Results

The SPF PV solar glass certification was introduced in 2012, and already more than 25 glass types have been certified and published, all of them achieving a first-class rating. In order to illustrate a few details of the three performance factors, as well as highlight some differences between standard methods of measurement and those of the adapted certification scheme, a selection of different typical types of glass was examined:

1. Thin float glass.

2. 'Thick' float glass (5mm) with iron contamination.

3. Lightly structured glass.

4. Same as 3, but with an AR coating.

5/6. Two glass types having a structured surface (prismatic).

Table 3 presents a summary of the different glass types measured: the results from the PV certification scheme (right columns) are compared with the results from the conventional solar thermal (TH) certification scheme (left columns). One major difference is that the PV transmittance factors are about 4% higher than the TH transmittance factors based on a conventional measurement in air. Another major difference lies in the IAM factors of heavily structured glasses. The different prismatic structures of glass nos. 5 and 6 have a negative influence on the conventional TH IAM factor measured in an air–glass–air setting. On the other hand, the IAM factors for these two glasses in the PV case (with no reflection at the glass back side) is slightly greater than unity, which means that their efficiencies at elevated incidence angles are slightly higher than that of the reference cell only (flat EVA front surface). Some of these effects will be explained in more detail in the

Class	Classification criteria				
P1			$\eta_{GL,PV}$	≥	0.940
P2	0.940	>	$\eta_{GL,PV}$	≥	0.925
P3	0.925	>	$\eta_{GL,PV}$	≥	0.910
P4	0.910	>	$\eta_{GL,PV}$	≥	0.890
Non-solar glass	0.890	>	$\eta_{GL,PV}$		

Table 1. Classification of untreated glass.

Class	Classification criteria				
R1			$\eta_{GL,PV}$	≥	0.980
R2	0.980	>	$\eta_{GL,PV}$	≥	0.965
R3	0.965	>	$\eta_{GL,PV}$	≥	0.950
R4	0.950	>	$\eta_{GL,PV}$	≥	0.925
Non-solar glass	0.925	>	$\eta_{GL,PV}$		

Table 2. Classification of single-sided AR-treated glass.

No.	Surface structure	Thickness [mm]	$\eta_{GL,TH}$	$F_{\tau,TH}$	$F_{IAM,TH}$	$F_{UV,TH}$	Class	$\eta_{GL,PV}$	$F_{\tau,PV}$	$F_{IAM,PV}$	$F_{UV,PV}$	Class
1	Flat, thin	3.2	0.906	0.909	0.997	1.000	U1	0.943	0.944	0.999	1.000	P1
2	Flat, thick	5	0.886	0.888	0.997	1.001	U2	0.924	0.928	0.995	1.001	P3
3	Light structure	3.2	0.911	0.916	0.996	0.999	U1	0.953	0.955	0.999	0.999	P1
4	Light structure, AR	3.2	0.942	0.940	1.002	1.000	Y1	0.995	0.985	1.010	1.000	R1
5	Prismatic structure 1	3.2	0.852	0.914	0.932	1.000	U4	0.954	0.952	1.002	1.000	P1
6	Prismatic structure 2	3.2	0.884	0.915	0.966	1.000	U3	0.957	0.954	1.003	1.000	P1

Table 3. Examples of glasses with different surfaces.

next section, by showing real measured data of the individual performance characteristics.

Transmittance

In Fig. 7 the BIC transmittance spectrum of a typical solar glass (no. 3) is compared with the conventional transmittance spectrum measured in air. As explained above, the reflectance in air and the reflectance spectrum with an optically coupled light trap have to be measured as well; both spectra are also plotted in Fig. 7. Within the important range of 0.4–1µm, as indicated by the weighting spectrum (C-Si@AM1.5), the extinction in the glass body is small. For this reason, the difference between BIC transmittance and conventional transmittance consists mainly of the reflectance at the back side, which is also the difference between the reflectance in air and the reflectance with a light trap.

To accurately calculate the BIC transmittance, both the extinction in the glass body and the multiple reflections between the glass surfaces are taken into account. The effect of extinction can be seen in the spectral region just above 0.3µm, where the BIC transmittance is higher than the conventional transmittance even though the reflectance in air approximates the reflectance with a light trap.

“To accurately calculate the BIC transmittance, both the extinction in the glass body and the multiple reflections between the glass surfaces are taken into account.”

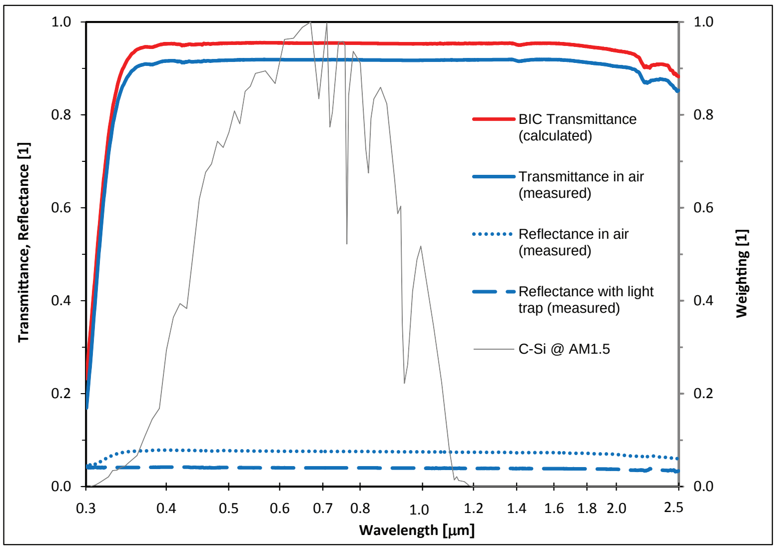

Figure 7. Calculation of the BIC transmittance spectrum from three direct measurements: transmittance spectrum in air, reflectance in air, and reflectance with an optically coupled light trap. As indicated by the weighting spectrum (C-Si @ AM 1.5), it is mainly the transmittance in the range 0.4µm to 1µm that is of importance.

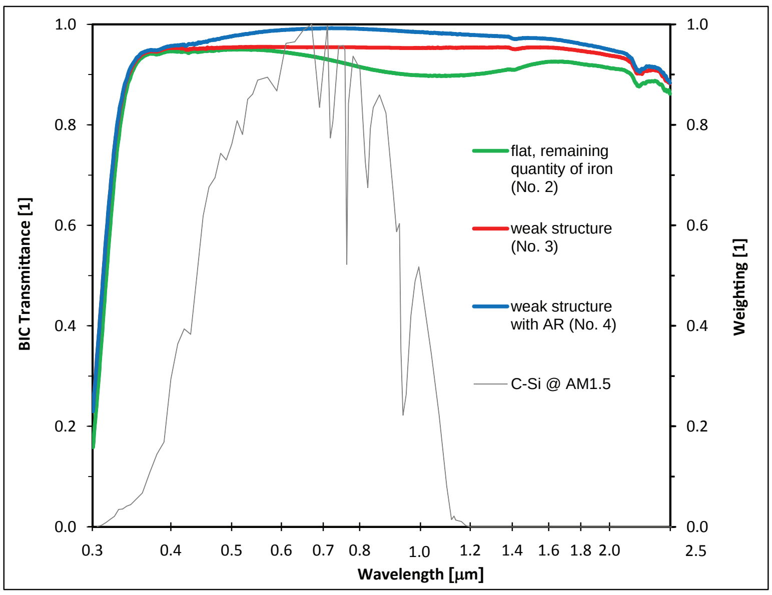

Figure 8. Comparison of the BIC transmittance spectra of a typical solar glass (no. 3), an AR-coated glass (no. 4) and a solar glass with iron contamination (no. 2).

Fig. 8 shows a comparison of the BIC transmittance spectrum of the typical solar glass (no. 3) with the spectra of the AR-coated glass (no. 4) and the glass with iron contamination (no. 2). The effect of the AR coating is tailored to the sensitivity of crystalline silicon cells. The BIC transmittance spectrum reaches its highest level (just less than one) at the centre wavelength of the weighting spectrum (C-Si@AM1.5) at ~0.65µm. The good matching of the AR coating to the cell sensitivity results in the high value of the weighted transmittance ($F_{\tau,PV}$) of 0.985 for glass no. 4: this means that only 1.5% of the usable incident solar light is lost by reflection or extinction caused by the glass, which is a very good value.

On the other hand, the spectrum of glass no. 2 shows a wide extinction band centred around ~1µm, which is typical for Fe^{2+} ions [5]. This extinction affects the sensitivity range of crystalline silicon cells and therefore has a negative influence on the PV transmittance factor ($F_{\tau,PV}$): for the example given (glass no. 2), it is reduced to 0.924 (Table 3).

IAM

Figs. 9, 10 and 11 show the IAM measurements for three glass types: a thin float glass (no. 1), an AR-coated glass (no. 3) and a glass with a prism-like structured surface (no. 6). For each case, the IAM measurement for the PV application (glass optically coupled to the detector) is compared with a conventional IAM measurement in air. The huge difference resulting from the reflection at the back side of the glass in the conventional case can be seen from the difference in the chosen references. In the conventional case, the theoretical value for a flat glass with a front and a back side is used (as reported by the French physicist and engineer Augustin-Jean Fresnel). In the PV case, a measurement of the bare detector without glass serves as the reference, which closely matches the theoretical value of a single glass front surface [1]. As seen in Fig. 9, in the case of a flat solar glass (no. 1) the measured curves almost reach the associated reference curves, resulting in IAM factors close to unity (0.997 for TH and 0.999 for PV).

The measured IAM values of an AR-coated glass (no. 4) have been plotted in Fig. 10. For both the thermal and PV cases, the curves are slightly higher than the reference curves, resulting in IAM factors greater than unity (1.002 for TH and 1.010 for PV). This means that an AR coating increases the electricity production not only by the increase in normal transmittance, but also by a better performance at high incidence angles. For the given example glass and the above-described reference solar plant, the better IAM performance as a result of the AR coating leads to an additional electricity production of ~1%.

A major difference is observed in Fig. 11 for glass no. 6, with the heavily structured surface (prism structure), which leads to low IAM values in the conventional case. On the other hand, the same prism structure has a positive effect on the IAM behaviour in the PV case. This inconsistency results in a serious misjudgement when a conventional glass-in-air measurement is used for the assessment of glass quality in the PV industry.

UV degradation

Most types of modern solar glass do not exhibit any UV-induced degradation and therefore all the sample glasses (from Table 3) indicate a UV degradation factor close to unity. An interesting effect, however, is observed for the glass with iron contamination (no. 2). As can be seen in Fig. 12 the transmittance (in air) at the absorption band of Fe^{2+} around 1µm is slightly higher after 250h of UV exposure. On the other hand, the transmittance is lower in the short-wavelength range of the spectrum, between 0.39 ptm and 0.49 ptm. The increase in extinction matches the absorption band of Fe^{3+} at around 0.379 ptm [5], showing the occurrence of a photo-oxidation from Fe^{2+} to Fe^{3+} during UV exposure. For the transmissivity the two effects counteract each other, but as the Fe^{2+} absorption better matches the cell sensitivity the transmittance is slightly increased for this example (+0.1%). Similar effects can have a negative effect on the glass transmittance, especially when cerium (Ce^{3+}) is involved.

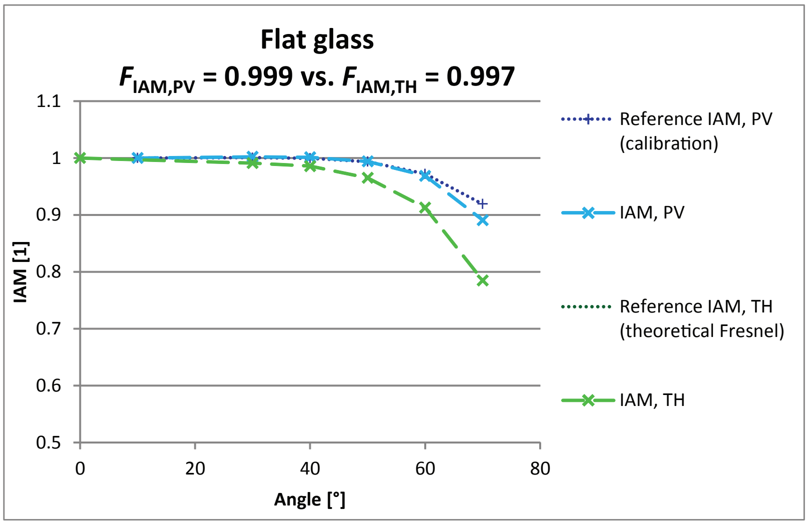

Figure 9. Comparison of conventional and novel PV IAM measurements of a typical flat solar glass (no. 1).

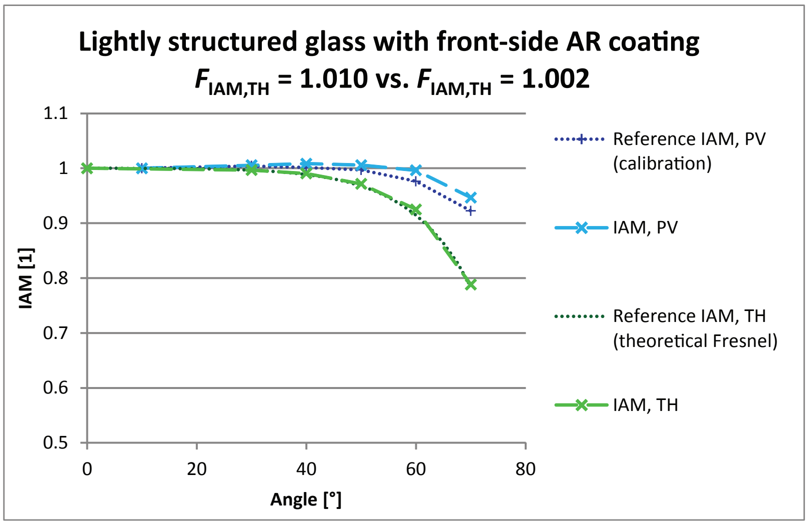

Figure 10. Comparison of conventional and novel PV IAM measurements of an AR-coated solar glass (no. 4).

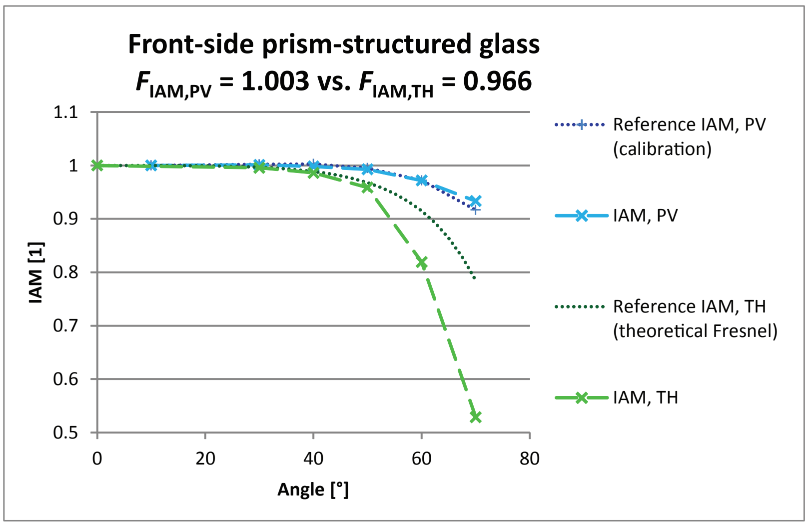

Figure 11. Comparison of conventional and novel PV IAM measurements of a prism-structured solar glass (no. 6).

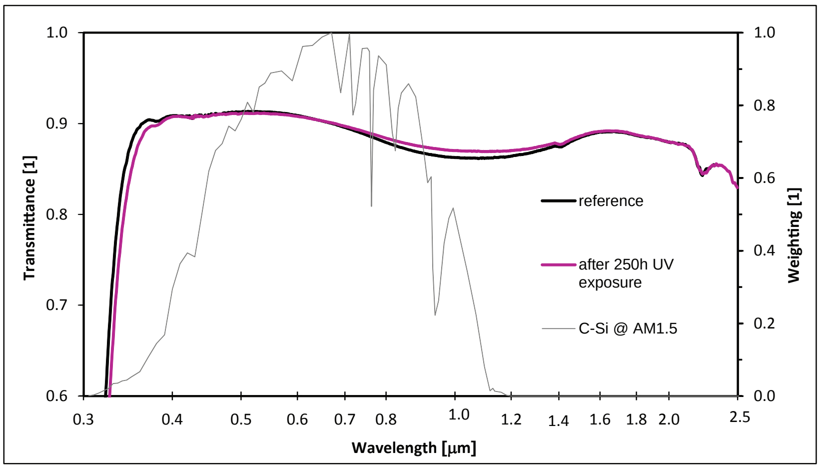

Figure 12. Comparison of the conventional transmittance spectra of a solar glass with iron contamination (no. 2) before and after UV exposition. The change in spectral transmittance is caused by photo-oxidation of Fe^{2+} to Fe^{3+} and leads to a slight increase in the transmissivity.

> "Good AR coatings lead to better IAM behaviour and result in an additional annual yield of approximately 1%."

Conclusion

The direct lamination of cells to the back side of the glass cover virtually eliminates the reflection at the glass back side. This effect is not taken into consideration by conventional glass measurements. Instruments and methods for characterizing transmittance as well as IAM by taking account of the eliminated reflection at the glass back side have therefore been introduced. From the analyses of more than 25 certified glasses and additional characteristic glass types, the following conclusions have been drawn:

- Losses caused by reflection and extinction of a good (i.e. low iron) standard glass cover sheet (nos. 1, 3, 5 and 6) only account for about 5% of the annual yield of a typical PV plant in central Europe.
- When good AR coatings are used, only 1.5% of the usable sunlight is lost because of reflection and absorption of the glass.
- Good AR coatings lead to better IAM behaviour and result in an additional annual yield of approximately 1%.
- The influence of the front-side structure on the IAM behaviour of a typical module is minor (which is contrary to the case of thermal collectors). Heavily prism-structured glass even tends to slightly increase the annual yield.
- The transmissivity of today's solar glasses does not tend to decrease because of UV exposure, unlike what was observed to be the case around ten years ago.

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About the Authors

Stefan Brunold is currently the deputy director of SPF-HSR in Switzerland, having previously been the head of the materials and optics department from 1993 to 2003. Prior to that (1990–1992) he worked as a scientist at FhG-ISE, where he focused on transparent insulation materials. Stefan was responsible for the development of the 'SPF Solarglass Certificate' (for solar thermal collectors), which was introduced as a new SPF service to the industry in 2001.

Florian Ruesch graduated in 2006 from EPFL in Switzerland and then worked at PMOD/WRC in Davos. Since 2007 he has been a project leader at SPF-HSR, with a special interest in optics and solar glazing materials. Florian was responsible for the adaptation of the 'SPF Solarglass Certificate' for PV applications in 2012.

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Power Generation

Indian government moots four giant PV projects totalling 2GW

India's finance minister, Shri Chidambaram, announced 2GW worth of new large-scale solar projects as part of his interim budget speech in February.

The finance minister said following the success of India's JNNSM national solar mission, the government wanted to see four "ultra mega solar power projects" each with a capacity of over 500MW in 2014-15. According to local press reports, the projects will be in Rajasthan, Gujarat, Jammu and Kashmir and form part of the JNNSM.

Plans are already underway in India for a multi-stage 4GW ultra mega solar power project in Rajasthan.

Source: Tata Solar Power.

India's government wants to see four PV plants totalling 2GW built by 2015.

US large-scale PV

California gives nod to 485MW Blythe PV project

The California Energy Commission has given approval for NextEra Energy's Blythe Solar Power project to switch from parabolic trough technology to photovoltaic.

The technology change was approved with a five to none vote, after NextEra proposed amendments to the land mass area and generation size of the project, scaling it down from 1GW to 485MW.

The original 1GW was approved in 2010 to be built on 7,043 acres of land from the US Bureau of Land Management.

The downsized 485MW is to span a 4,070 acre site, to be constructed in three phases of 125MW, and a final phase of 110MW.

Duke issues request for 300MW of PV in Carolinas

The largest electric holding power company in the US, Duke Energy has issued a request for proposals (RfP) for 300MW of solar.

The RfP was issued for projects in Duke Energy's Carolinas and Progress territories, which includes North and South Carolina and Florida.

Any proposed solar plants should be operational by 2015; bidders can offer power, renewables certificates or whole projects for Duke Energy to take ownership. Projects must be over 5MW in capacity, and the proposal only applies to projects already in Duke Energy's transmission and distribution queue, to assure completion by 2015.

National Solar Programmes

Germany's solar industry issues warning as government mulls 2.5GW annual PV cap

Germany's solar industry has warned that proposed changes to the country's renewable energy support could damage its standing in the sector and block one route to secure, low-cost energy.

Bundesverband Solarwirtschaft (BSW-Solar) claimed in an open letter to Chancellor Angela Merkel, that a proposed charge for self-consumption could lead to "another photovoltaic market slump".

A document leaked to the press reportedly showed that the government is keen to establish an annual cap on new annual installed PV capacity of 2.5GW with the same limit attached to onshore wind.

BSW-Solar agrees with the need to phase-out the support provided by the Energiewende (EEG) policies, it said the levy on self-consumed solar would have the opposite effect.

Brazilian state approves 123MW of solar developments in energy auction

The Brazilian state of Pernambuco has approved 122.82MW of solar projects after hosting the country's first solar-only tender auction. Competing in the auction were 34 project bidders – six from Brazil along with others based in China, Germany, Italy and Spain.

The largest of these six successful tenders was won by Sowitec for a 30MW solar plant, closely followed by Sun Premier Holding Participações, which won a 29.75MW bid, and Kroma Comercializadora de Energia, which won 29.25MW.

Concierge Cone S/A has been commissioned to build 22.82MW and Enel Green Power two 5MW projects.

Pakistan announces long-awaited upfront solar FiT rates

Upfront FiT rates for large-scale photovoltaic projects in Pakistan have been announced by the country's National Electric Power Regulatory Authority.

The newly announced FiTs will apply to plants of between 1MW and 100MW capacity and are set at a different rate in the north and south of the country, with historically higher levels of solar irradiance recorded in the south of Pakistan than the north.

NEPRA referred to the division as a 'tiered tariff structure' and described the system as "ideal" due to "the solar irradiance profile of Pakistan". The tariffs are calculated as a payment to cover 25 years of operation.

Moroccan government denies investors are shunning US$9 billion solar project

The Moroccan government has denied that all investors are shunning a US$9 billion solar project in the Western Saharan region following reports that banks were shying away from the disputed territory.

There are plans for five huge solar projects and three of them, totalling 1.1GW in capacity, are in or border with the Western Sahara. An Algerian-backed group is seeking independence for the region. At the turn of the year Reuters reported that a number of major banks were putting investments in the area on hold.

Source: Andy Colthorpe.

Unbuilt FiT-qualified PV projects in Japan have been given more time before facing the axe.

Spain's FiT replacement scheme cuts PV support by 25%

Spain's antitrust authority Comisión Nacional de los Mercados y la Competencia (CNMC) has revealed the scale of cuts in support for solar farms, estimating that between €550-600 million (US$743-811 million) a year will be saved by the Spanish government thanks to the replacement of the feed-in tariff system.

The Union Espanola Fotovoltaica (UNEF) has calculated that the new regime, which limits profitability to 7.5%, represents an average cut of 25% compared to what an installation would have made from the FiTs. Larger systems over 10MW face reductions in excess of 40%.

Stay of FiT execution for Japan's unbuilt solar projects

Companies responsible for 748 Japanese solar power projects that have gained approval to receive the feed-in tariff (FiT) but have not yet been built have been handed a temporary reprieve.

The Japanese Ministry of Economy, Trade and Industry (METI) has now ruled that developers of the projects, which include a number of so-called 'mega' projects of above 1MW, will be given until either March or August to get paperwork pertaining to land rights or equipment accreditation in order.

Industry Outlook

IHS: South Africa most attractive emerging solar market

South Africa has been rated the most attractive emerging PV market in a quarterly report for global information company, IHS.

South Africa scored 66 out of 100 when analysed for macroeconomic climate, market size potential, profitability and pipeline maturity, alongside other emerging markets. South Africa topped the chart thanks to the country's solar targets and the favourable tender process of its national renewable energy programme, which has attracted significant solar investment.

Report: MENA solar to be worth US$50 billion by 2020

The Middle East and North Africa could see investment in solar reach US$50 billion by 2020 as governments push to exploit the region's huge resources, research claims.

A report published by business intelligence firm MEED Insight in conjunction with the Middle East Solar Industry Association (MESIA) estimates that up to 15GW could be built in the region by 2020 as part of a much bigger drive towards renewable energy.

While the region had only a small 217MW of solar installed as of this month, the report predicts this situation will change "radically" over the next few years as governments "embrace" renewables.

Restructuring

Martifer Solar USA files for Chapter 11 bankruptcy

Martifer Solar USA, the US arm of Portugal based PV developer Martifer Solar, has filed for Chapter 11 bankruptcy with a Nevada court following failed negotiations with creditors, the company said.

The company had estimated assets of US$10 million to US$50 million. The claims deadline for creditors is 21 May. Martifer Solar USA volunteered for reorganisation and said the company could meet obligations to third parties, although it would need to adjust its repayment schedule. The bankruptcy only applies to Martifer Solar USA, 55% of whose share capital is owned by Martifer.

Juwi cuts 80 jobs and pulls out of Spain as restructuring continues

German renewable energy developer Juwi has announced that as part of company-wide restructuring efforts, it will pull out of its Spanish operations and cut a total 80 jobs in Europe this year.

At the same time, short term and medium term businesses that are presenting the company with high financial costs will be outsourced or otherwise disposed of.

Around 50 jobs are expected to be cut from the company's operations in Germany and a further 30 employees will lose their jobs in other European countries. The company said Juwi employees in Spain were informed of the decision to cease trading in December.

Source: SMA/Scatec Solar.

South Africa's Kalkbult PV plant. The country has been rated the most attractive emerging solar market.

Product Reviews

ATI

Source: AMEC

ATI's DuraRack fixed-tilt system enables highest number of modules per post in the industry

Product Outline: Array Technologies' 'DuraRack' fixed-tilt racking solution has incorporated several key features from the company's 'DuraTrack HZ' single-axis tracking system designed to reduce installation times and balance of system (BOS) costs.

Problem: Reducing PV power plant BOS costs in respect to module mounting systems can be achieved with higher emphasis on pre-engineered and pre-constructed components. Minimizing overall component usage and increasing the number of modules mounted per post are also areas for cost reduction.

Solution: The DuraRack fixed-tilt racking system now includes integrated grounding, pre-installed on each module mounting clamp. The hardware eliminates the need for additional module grounding hardware or wire and eliminates time required to ground modules without an increase in price. The universal module mounting clamps are now part of the fixed-tilt racking system, offering customizable tilt angles between 10° and 40°. In addition, the DuraRack can rack modules in portrait or landscape configurations to maximize ground coverage ratio (GCR).

Applications: Fixed ground-mounted PV power plants.

Platform: ATI claims DuraRack offers one of the highest number of modules per post (12) in the industry – a key benchmark for fixed-tilt comparisons since foundations tend to increase BOS cost. DuraRack's array structure resembles a flexible spine, where module mounting beams may be positioned higher or lower at each support column, depending on terrain undulation.

Availability: February 2014 onwards.

Locus Energy

Locus Energy offers PV system fleet operators enhanced data collection

Product Outline: Locus Energy has introduced its next generation of smart meters designed to allow solar installers and asset managers to more easily collect, monitor and analyze performance data from both residential and light commercial solar PV systems. The LGate 120 and 320 are said to be the first cellular smart meters designed specifically to measure the performance of PV installations.

Problem: Until recently, the cellular socket meters available for PV monitoring have mainly been repurposed utility meters that have focused on consumption and demand rather than PV industry requirements. A low-cost, feature-rich and easy to install meter that can be installed on many different types of PV systems is required to reduce installation O&M, BOS and 'soft costs.'

Solution: Both units can communicate directly with inverters to collect additional AC and DC data points as well as fault code information, which is key to lowering O&M costs over a fleet of systems. In addition, the new meters can plug directly into local area networks via ethernet when the cellular signal is not strong enough at a given location.

Applications: Meter/data-loggers for residential and commercial PV systems.

Platform: The LGate 120 is a one-piece completely under glass meter which installs easily using a standard socket base. The LGate 320 is a three-phase electronic watt-hour meter for remote monitoring of light commercial solar PV systems. Both combine a revenue-grade, solid-state power meter with an advanced communications gateway.

Availability: Currently available in the US.

Alectris Solar

Source: BP

Alectris Solar provides O&M analysis tool for PV project owners

Product Outline: Alectris, a global operations and maintenance (O&M) independent service provider for distributed generation and utility-scale solar PV plants in North America and Europe, has unveiled a new 'Alectris Solar PV Owners O&M Evaluation Tool' for solar asset owners to evaluate their O&M priorities and contractors.

Problem: The performance of an O&M contractor is tightly connected to the asset's performance optimization, yet the evaluation of the contractor's capability to perform and even excel in the contractual obligations is a more complex process.

Solution: The Alectris Solar PV Owners O&M Evaluation Tool was developed for solar asset owners to prioritize their O&M needs and evaluate their contractors. It will assist in the standardization of this process and the industry's overall best practices development and currently includes 85 discrete items related to the basic functions of operations and maintenance for solar PV plants.

Applications: Commercial and utility-scale PV power plant O&M analysis.

Platform: The new tool offers a holistic, unified approach to evaluating O&M considerations and capabilities. It includes features such as self-determined priority setting and O&M contractor evaluation scores which are then mapped to the owner priorities. Solar PV O&M key performance indicators are also mapped to O&M contractor capabilities. A customizable tool provides the opportunity to add more evaluation areas, while a graphic depiction of contractor scores are automatically built into the tool.

Availability: February 2014 onwards.

Product Reviews

Enphase

Enphase offers simpler microinverter installation and operational software management

Product Outline: Enphase Energy has introduced new hardware and software products that are claimed to lower solar system installation and operations costs for solar professionals. New hardware includes a Wi-Fi option for the 'Envoy Communications Gateway' and 'M215' microinverter with 'Integrated Ground.' 'MyEnlighten' and 'Enlighten Manager,' are also available.

Problem: Reducing PV rooftop installation times has a direct impact on the overall levelized cost of electricity. Providing simpler and cheaper ways to monitor operating PV system can provide improved customer awareness of energy consumption and overall product investment satisfaction.

Solution: Based on Enphase's fourth-generation microinverter platform with 96.5% CEC efficiency, the new M215 includes Integrated Ground technology that eliminates the need for a grounding electrode conductor to be attached to each microinverter, providing labour and materials savings, according to the company. A Wi-Fi option for greater flexibility when choosing where to locate the Envoy Communication Gateway is also included. All systems reporting through the Envoy are visible in the web-based Enlighten software platform.

Applications: Residential and commercial rooftops.

Platform: Enlighten Manager provides PV professionals with sophisticated web-based software tools that can effectively prioritize maintenance needs across multiple installations. These tools and an interface designed to manage multiple customers are claimed to provide greater control over operations costs.

Availability: Currently available.

Praxis Resources

Praxis Resources meets demanding PV field testing with IV curve tracers

Product Outline: Praxis Resources has launched the PCT-1800 IV Curve Tracer. The unit is shock resistant, easy to operate and user friendly. The large-scale 10.4" color touch panel LCD and integrated computer are key to generating IV curves, completing PV array performance analysis and producing immediate performance feedback, according to the company.

Problem: Most IV Curve Tracers are not able to test to 1800 Volts and 50 Amps. Large-scale solar fields require an all-in-one test system that is robust and user-friendly, and a screen that can be seen in direct sunlight.

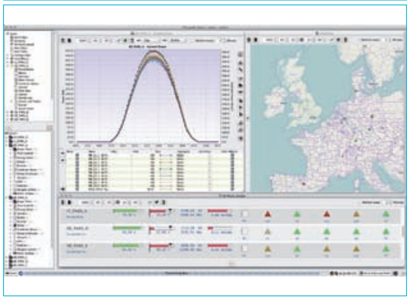
Solution: The PCT-1800 is a self-contained testing device that creates a fast curve and is capable of generating up to 2,000 curves between charges. The device provides the advantages of faster analysis, less down time and greater profitability. The auto-ranging system sets the voltage and current gain selections during operation, assuring the best possible performance. The system provides 1,000 points per trace and provides comprehensive test reporting. Praxis will customize the unit as requested.

Applications: PV field testing, warranty and reliability verification.

Platform: The PCT-1800 is built into a rugged all-weather case that can withstand the rigours of air travel and daily use. It operates at high power: 0-1,800 Volts at 1%, .5 – 50 Amps at 1.5%. Operating temperatures from range from -20°C (-4°F) to 60°C (140°F); 120 volt, 12 volt adapters, auxiliary analog input and integrated computer with atom dual core processor provide maximum performance. Built-in reverse voltage and over voltage protection delivers enhanced safety. Twelve gigabytes of data storage and high resolution GUI make the unit easy to operate in the field.

Availability: Currently available.

Skytron



Skytron adds performance and planning enhancements to 'PVGuard' power plant software

Product Outline: Skytron energy has made considerable performance upgrades to its monitoring, control and supervision solutions for PV power plants. The 'PVGuard' Supervision Platform has been enhanced with improved SCADA software capabilities for energy production planning, performance analysis and system integration.

Problem: PV power plant management has evolved due to changing market conditions. In particular, the opening of the energy market for direct trading on electricity exchanges and the volatility in the investment sector are creating demand for more versatile forecasting tools.

Solution: Skytron SCADA software enhancements enable production forecasts for strategic grid and market integration to be finely tuned several times a day. Production forecasts supplying estimates of hourly production for up to seven days in advance are provided. A new 'FlexReportXL' report generator produces plant performance reports that can include information from other sources, such as forecasts from the yield assessment report, and customers' own calculations can be incorporated in the automatic report. FlexReportXL allows the generation of multiple reports of different content as well as their e-mail dispatch at selectable intervals from an hour to a year.

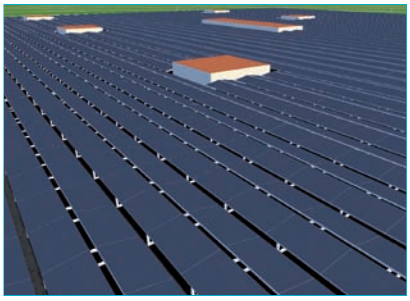
Applications: Monitoring, control and supervision of PV power plants.

Platform: Grid connection specifications of some countries insist on a reliable prognosis of the power available for grid injection. In PVGuard, an auto-adaptive algorithm predicts the power production on the basis of current weather data, plant characteristics and the output over recent weeks.

Availability: January 2014 onwards.

Product Reviews

Valentin



Valentin Software offers updated shading capabilities up to 2MW sized projects

Product Outline: Valentin Software has released the PV SOL Expert 6.0 R7 edition, enabling users to plan and visualize roof-integrated, rooftop and free-standing PV power plants with a power of up to 2MW.

Problem: PV system shading and prevention remains a key problem in evaluating overall system performance expectations. Variability in the ways shading analysis is undertaken can introduce errors or lead to conservative layout and reduced ROI.

Solution: PV*SOL Expert 6.0 R7 allows users to analyse shading in detail in a 3D mode. The software calculates how often modules are shaded on average, delivers concrete information on how shadows are cast at different times of the day and year, determines the loss in yield and shows the results graphically. For the first time, the software can also simulate the influence of any power optimiser chosen. As a further innovation, the software has now received an interface to the program k2base for the designing of mounting systems. All of the information can be exported as XML files and processed directly for the assignment of as many roof surface areas as desired.

Applications: Dynamic simulation program with 3D visualization and detailed shading analysis of roof-integrated or mounted grid-connected photovoltaic systems.

Platform: In all its versions PV SOL has a well-maintained database with more than 13,000 solar modules and around 3,100 inverters, which is automatically updated and expanded. All of the PV*SOL versions are available in German, English, French, Italian and Spanish.

Availability: January 2014 onwards.

Schneider Electric

Schneider Electric's Conext Core XC-NA Series central inverters provide harsh environment reliability

Product Outline: Schneider Electric Solar Business is now shipping the new Conext Core XC-NA Series central inverters, designed for high reliability and compatibility with any PV panel type and installation.

Problem: With the majority of large-scale PV power plants located in harsh environments, operators and owners require central inverters to operate consistently with high reliability and low maintenance.

Solution: The Conext Core XC-NA Series central inverter is said to have undertaken extensive safety, quality and reliability testing, including dust, rain ingress, seismic and salt spray to ensure a very robust product. The inverter is CSA Certified to UL1741 and CSA C22.2 no.107.1 to 1000 VDC and comes with integral AC and DC switchgear which meets the requirements of NEC 690.17. In addition, the Conext Core XC-NA comes with an integrated DC combiner with a variety of fuse and monitoring options and a next generation ground fault detection system. The inverter has a 98.6% peak and 98% CEC efficiency rating with a wider range of full power operation from -20°C to 50°C, with -35°C option. Static and dynamic MPPT efficiency is over 99.9% (Tested to EN50530).

Applications: Centralized PV plants.

Platform: The Conext Core XC-NA can be provided as part of a skid-mounted or PV box solution. It has integrated AC and DC switchgear using Masterpact NW circuit breakers, which meet the requirements of NEC 690.17. It comes with configurable firmware to allow for easy adjustments to changing utility requirements.

Availability: February 2014 onwards.

SolarMax

SolarMax HT string inverters provide multi-tracking for optimum PV system yields

Product Outline: SolarMax has introduced a new range of HT string inverters with multi-tracking – designed to deliver optimum system yields for operators of commercial and industrial PV power plants. The SolarMax HT series will be available in three models: 30 kW (30HT4) and 32 kW (32HT4) output, each with four MPP trackers, and 32kW (32HT2) output with two MPP trackers.

Problem: In the face of continuing reductions in subsidies, PV plant planners have the challenge of delivering cost-optimized systems which will provide high levels of availability and efficiency and increase returns.

Solution: The HT series string inverters employ multi-tracking to provide the optimum operation of each individual part, even with highly complex PV system configurations and partial shading. In this way, the yield from the available surface area can be optimized.

Applications: Commercial and industrial rooftop PV installations.

Platform: HT inverters are designed for quick and easy installation. The high output density and compact dimensions minimize space requirements while also reducing AC wiring. If external DC switches and surge arresters are required, the 32HT2 model comes with the additional functionality of a terminal box which can give further cost efficiencies for plant engineers. The terminal box contains the DC switch, the surge arresters and the string fuses. The HT series are also equipped with the latest communication and monitoring solutions, and are easily incorporated into the MaxView web portal for location-independent monitoring.

Availability: February 2014 onwards.

PV's plug-in power plants: How modular design is cutting the cost of solar electricity

Mark Osborne, Senior News Editor, *Photovoltaics International*

ABSTRACT

The pioneers of utility-scale PV construction have drawn on methods used in other industries to make power plants more efficient and more competitive. This paper investigates how cutting-edge techniques in modular design are being used to drive down plant costs. The evolution of modular design and its attractiveness to the investor community are discussed.

Introduction

Large-scale solar PV power plants hold the promise of providing PV-generated electricity at the lowest levelized cost of electricity (LCOE) and therefore becoming the first among PV end-market sectors to reach real-world grid parity and beyond. Production scale in upstream PV manufacturing has been a major factor in solar installation cost reductions over the last decade, and now the drive to scale in the downstream ground-mounted PV power plant sector is generating further overall cost reductions. In less than a decade, PV power plants have gone from the 1MW scale milestone to recent plans to achieve combined/adjoining projects of 500MW and above.

But the rapid development of PV power plants has also resulted in the need to move away from bespoke construction techniques and apply industrial manufacturing methodologies to PV power plants. As projects in the multi-megawatt range have increased, economies of scale have enabled PV power plant pioneers to not only look at scaling benefits simply from a component purchasing perspective but also take a holistic approach to all phases of construction, from pre-planning through to power plant monitoring.

Matt Campbell, Senior Director of US manufacturer SunPower, explains how it treated every project as different and unique when the company first

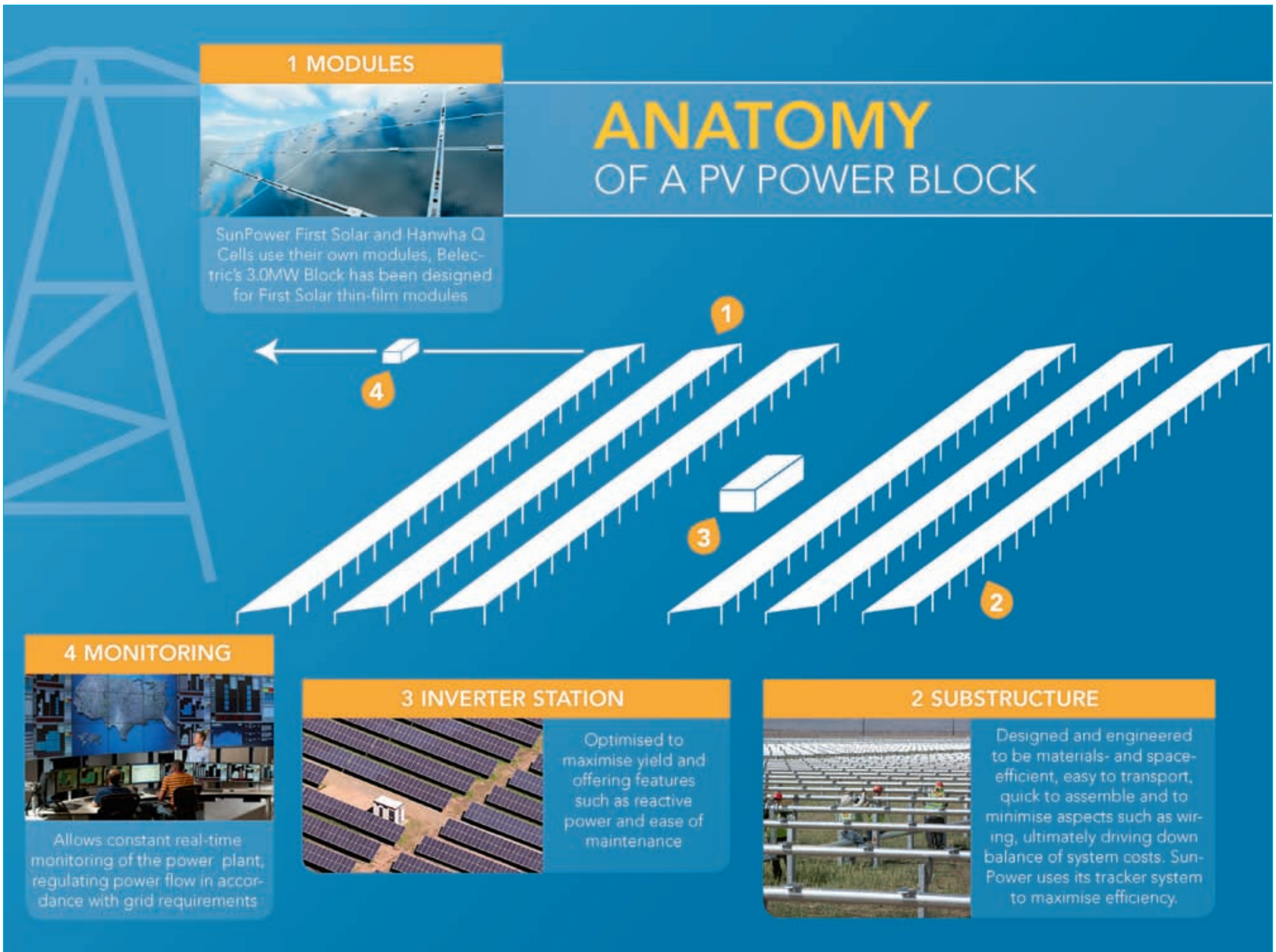


Figure 1. The main elements of a modular PV power block.

Infographic: Viki Hämmerle, Solar Media.

got involved in PV plant construction. "When we thought about scaling this business to tens of megawatts and hundreds of megawatts, which had always been part of our mission, we thought we needed to cookie-cutter this," Campbell says. "We had to really reduce costs both in the product [panels] and in the field with installations and to standardize."

Modular platform evolution

SunPower is one of a number of leading players in PV manufacturing and large-scale plant construction which are increasingly taking a modular, standardized approach to plant design in a bid to drive down LCOE. This approach has its roots in other forms of complex, high-volume manufacturing, such as automotive assembly, which is well known to have adopted standardized production techniques to reduce overall costs.

The main components of a PV power plant are the solar PV panels, fixed mounting (or tracking) systems, cabling, inverters, transformers, grid connection and plant monitoring. Bringing disparate components to a single site, often with major components such as the panels and central inverters shipped from different continents, involves a high level of complexity, but, because of the scale, also provides significant opportunities to drive down costs.

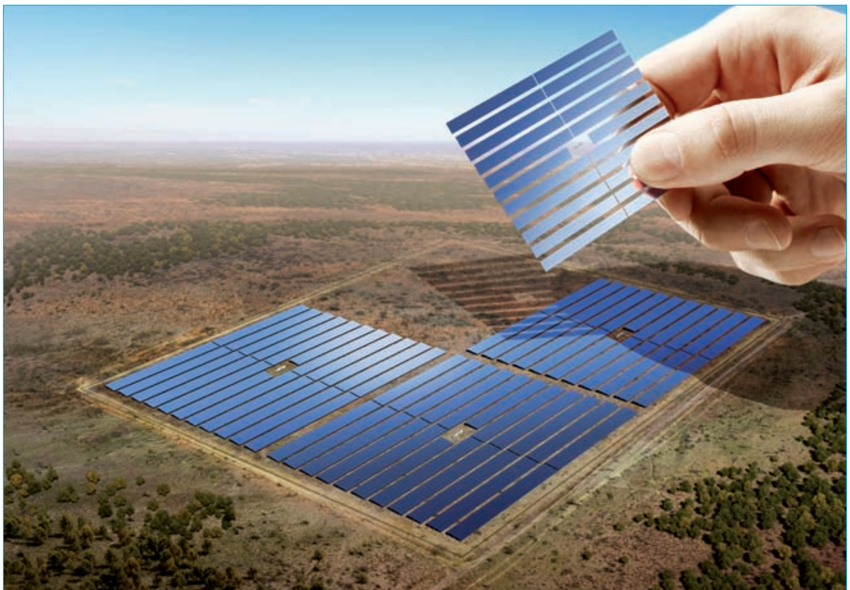
It is no coincidence that several leading PV cell/module manufacturers – such as First Solar, SunPower and Hanwha Q CELLS – have been quick to take a lead in PV power plant design, bringing their high-volume upstream manufacturing methodologies to PV power plant design. The move downstream is now being widely adopted, not just by other PV module manufacturers but also by enterprises in supply sectors further upstream, such as polysilicon producers like SunEdison, formerly MEMC, and GCL-Poly.

"First Solar strategically vertically integrated in order to reduce the cost of solar electricity and expand into markets without feed-in-tariff policy structures in place," notes Tom Kuster, Senior Vice President, Product Management and Systems Solutions at First Solar.

"By gaining engineering, procurement and construction capabilities, project development and finance capabilities, numerous balance-of-system technologies and industry-leading operations and maintenance expertise, First Solar became a vertically integrated turnkey PV power plant provider."

SunPower cut its teeth developing high-efficiency crystalline silicon cells, but is now a major provider of modular PV power plants, building its first megawatt system back in 2006. According to Campbell, after its revelation about taking a "cookie cutter" approach to plant design, SunPower developed its first branded modular system. "In standardizing we called it 'a power plant in a box', like buying furniture from Ikea. It went from being called a 'power block' to 'Oasis'," he says.

Meanwhile, although not a manufacturer per se, Germany-based EPC firm BELECTRIC is another pioneer of the modular approach, having realized early on that PV power plants needed to evolve beyond the individual customized approach. "With the reduction in the feed-in tariff and the pressure on costs we needed a different approach to serve the utility solar power plant sector," says Chief Executive Bernhard Beck.



Source: BELECTRIC.

Figure 2. BELECTRIC's '3.0 MegaWattBlock' is an example of how modular design is being used in utility-scale PV plants.

Modular PV power plant methodology

As well as car manufacturing, PV power plant pioneers looked to the wind turbine industry for a route to standardization. According to Campbell, SunPower created an integrated cost-reduction roadmap that took inspiration from both the automotive industry and the wind turbine sector. He notes that the 1.5MW wind turbine has been the workhorse of the wind industry for ten years; once the sector had standardized on a 1.5MW unit, the costs of the system were dramatically reduced.

Beck also highlights the influence of the wind industry. "The wind turbine is a defined product and as a project developer you would go around and find the right location for this product," he explains. "This is very logical and has been the practice in the wind industry for around ten years, and the solar industry had to adopt the same approach.

This approach was very clear as it didn't make sense to adapt a piece of high technology to a piece of land. We needed to turn this around and find the right piece of land for the technology, the same way the wind power sector does.

"Although cost reduction was a key driver for the modular block approach, lifetime expectations in the field could not be compromised. A standardized power block had to retain high levels of component quality and overall system quality."

Hanwha Q CELLS, via its former project developer arm, Q-Cells International, was another pioneer of the modular approach.

"We created our EPC business in 2007, underpinned by the pursuit of high quality from our manufacturing," says Frank Danielzik, vice president of EPC at Hanwha Q CELLS. "Quality, quality, quality was at the core of the approach as we had to guarantee to the power plant for 20 years. Right from the start we adopted a modular approach to every aspect of the project business. This included standardized documentation and procedures throughout."

According to SunPower's Campbell and others, the key to driving down costs through the modular block approach is 'pre-optimization' of all elements of the system.

"A power plant block is a complex engineering problem, as you are trying to optimize your manufacturing supply chain logistics, delivery of material, construction sequencing, material utilization, which could be the steel structures and the cabling, and then putting the kit together. Therefore the whole sequence has to be optimized, and when you standardize you can pre-design everything to work together as a seamless system; it becomes the most efficient way to build the system."

BELECTRIC takes this idea to its

extreme, designing every component in its power block as part of an overall system. Beck says: "Systems are designed as one thing. So, we do not use components we suddenly find on the market and combine them in a product; we design a product. That differentiates us from all the other players in the market; we design a product and then we produce the components needed for that product. Anyone else offering power blocks uses available components and brings them together in a product definition. The main difference is that we engineer the full thing."

LCOE motivations

Combining cost reductions and providing the system performance, while maintaining overall lifetime requirements, ultimately all come back to LCOE. The continued adoption of PV power plants will depend on this metric, as will the success of the modular block approach.

"We optimize the unit for the lowest LCOE and that includes the quality requirements for the unit to last the necessary 20–25 years. We know all the parameters and we focus on reducing the kilowatt hour cost. I am pretty sure that our 3.0 MegaWattBlock is the industry benchmark," says Beck, referring to BELECTRIC's flagship modular power plant product.

SunPower's Campbell claims: "Our modular approach is different in that it really is LCOE driven as opposed to cost driven. It's interesting that in the PV industry there has been a shift in the last three to four years from talking about cost per watt to LCOE. Yet we do see people revert back to cost per watt; it's a reflection of the complexity of LCOE. But we see it as important that customers really understand LCOE, which we are pleased our sophisticated customers do and see the long-term picture, and that's the theme of our modular approach."

First Solar's Kuster, meanwhile, says his company can deliver a LCOE that is cost competitive with conventional generation sources today. There is no question that for modular power plant pioneers the bragging rights to the lowest LCOE is hotly debated. However, is not the focus of this paper to directly compare and analyse which company and technology holds the lowest cost mantle. Rather, the focus is to understand how the modular block approach to PV power plant design provides the future of electricity generation.

Beck sums this up when he says: "With the modular approach everything comes together in LCOE comparison. This is where you have to educate the customer, as there are many ways to construct low-cost electricity. There are differences between products available from the few companies able to offer this approach, yet they all have to provide the necessary LCOE levels. Simply compare the products being offered against the LCOE."

Benefits of evolution

The benefit of a modular approach is that once a design is proven in the field across multiple projects, it can be tweaked to incrementally reduce costs further, taking LCOE economics into unchartered waters.

"One of the things that has been interesting has been that we have these operations built into our DNA, as we have built our own factories and our own production lines, and we have used lean principles that help us get waste out; and that's what we have done with our modular power blocks and plants," says Howard Wenger, SunPower's president of regions, who is responsible for the company's global residential, commercial, utilities and power plants business.

Wenger says that working on bigger projects also allows SunPower to make ongoing improvements to what it does. He cites one of the company's largest current projects, the 747MWp Solar Star project in California, which is being built around SunPower's Oasis platform, the brand name for its power block concept.

> "Any time we learn something at any stage it goes back into research and product development for the next developed product."

"With Solar Star we are using our second generation Oasis [platform] and between those generations we made a number of improvements – things like [increasing] the rate at which we can install from 1MW a day to 2–3MW a day, with the ability to go even faster," says Wenger. "The [Solar Star] plant will use around 500 modular Oasis lines, which will even allow for continuous improvements within one project."

BELECTRIC's Beck echoes this point: "Anything we learn from the product goes back into research. This is the difference," he remarks. "If you see a normal, individually built EPC power plant this is not a round ticket thing, rather it's a one-way ticket. Information learnt on an individual project may not therefore be usable on another project, especially when different modules or inverters are used.

"Where is the learning curve, compared to doing the same thing over and over again and getting better each time? Any time we learn something at any stage it goes back into research and product development for the next developed product. This is how we took our 2MW Block to the 3MW Block and the next stage beyond."

"Our modular approach in collaboration with our own R&D and systems department enables us to find room for improvement every year, while retaining the high quality," adds Danielzik from Hanwha Q CELLS.

The learning curve advantages that standardization provides do not necessarily have to be applied post-project. SunPower's Campbell highlights some examples of learning curve dynamics that were actually implemented during individual projects, albeit on some of the largest PV power plants built to date that have longer lead times.

"We have a closed-loop audit process integrated into the programme, especially on the construction side. As we get feedback in the field we loop that back to engineering and project development, and although we take a pretty rigorous approach to standardization there are areas of flexibility to adapt to real-world situations in the field," Campbell explains.

The SunPower Oasis (1.5MW) power block achieved an annual cost reduction (BOS) of 24% in 2013, according to the company in its fourth quarter, 2013 financial conference call. As seen in Fig. 3, which SunPower released in mid-2013, its Oasis cost reductions were projected to fall to the 50% range at the end of 2013. Off-field pre-engineered components – such as tracking and racking systems – have been key cost-reduction drivers. The company remains confident that the complete loop-forward and loop-back revisions strategy to the power block, which takes advantage of both engineering and technological advances, will provide further BOS cost reductions.

First Solar had also published a BOS and LCOE cost-reduction roadmap (see Fig. 4) in early 2013. The holistic approach to integrated system design and implementation of engineering upgrades and new technologies is also a key cost-reduction driver at the company. Improving overall power plant yield with a newly designed tracker system is part of the strategy, and that system also has its own BOS cost-reduction roadmap. First Solar has also been developing new techniques for installing its modules on the racking system in a much faster way than in the past.

Attractiveness to banks, investors and owners

Ultimately, though, the attractiveness of the modular approach has to resonate with the end customer and financial backers.

According to Beck, the market is still not really ready for what he describes as the "full delivery of solar power generation". What this means is that the ability to take a single modular power plant unit and place the product at a correctly selected site, like that undertaken in the wind sector, has yet to be widely understood by investors and PV power plant owners.

"However, what we see is the growing interest from the utility sector and the investment sector to invest in standardized solar power plant units," Beck adds. "These provide the certainty from one block to another, regardless of the number of blocks in a project.

"We know in advance what we are going to see in performance and LCOE, and we can provide pricing several years ahead. This all makes it easier when selecting the right site or placement options."

> "Providing a standardized turnkey approach has significant benefits for the end customer and related financial partners."

According to Hanwha Q CELLS' Danielzik, providing a standardized turnkey approach has significant benefits for the end customer and related financial partners. A key benefit is the transparency provided at every stage of the project, backed up by known and bankable high-quality products, processes and certification, which keeps all stakeholders informed and involved.

"The modular approach provides many benefits, but transparency, especially early on in a project, is often crucial," he says. "Standard processes with clear definitions and timetables enable successful project execution with quantifiable gates."

Danielzik also notes that adopting a complete modular approach to all aspects of the project means there are no surprises for customers or financiers and that final acceptance always turns out as planned.

"From an operations point of view there is a need to reduce unknowns so that 95% of issues are clearly answered in using the modular approach. The project-specific adjustments are limited to what is needed by the customer, which accounts for the remaining 5% and they are typically about actual site considerations," says Ron Stephan, head of engineering and construction at Hanwha Q CELLS.

SunPower's Campbell echoes this crucial factor: "One of the advantages of the standardized approach is the power block becomes a known entity to the investor and is all de-risked. It should be so well engineered that it becomes boring. From an investor point of view boring is good."

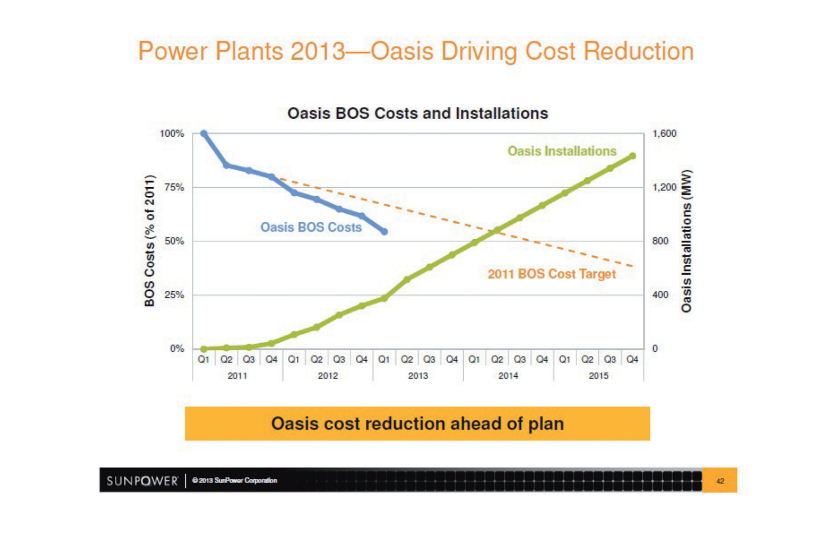


Figure 3. SunPower Oasis cost-reduction roadmap.

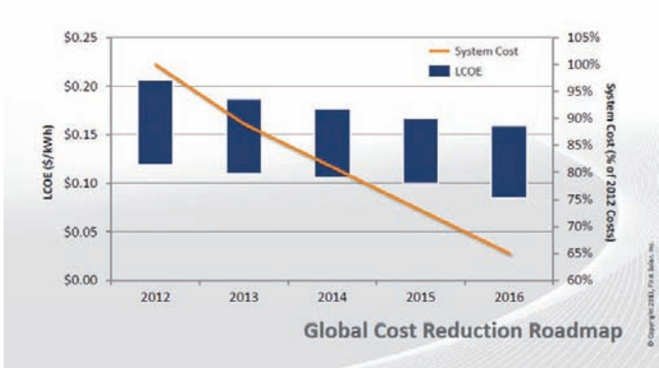


Figure 4. First Solar PV system cost-reduction roadmap.

Global capabilities

First Solar's Kuster adds a further spin on the theme: "The pre-engineered and configurable designs provide local construction partners with flexibility as they adapt the solution to meet local codes and project-specific parameters. The optimized and proven solution also serves to streamline project activities, including development, financing, permitting, installation, and commissioning for a faster time-to-power.

"By streamlining the execution of solar projects and providing local construction and supply chain jobs, this business model provides significant regional value while minimizing the technical risks associated with power plant execution and operation in emerging solar markets."

Certainly, Kuster is hitting on a major attraction of the modular approach that mirrors the overall PV trend of broad-based globalization. Large-scale PV power plants have predominantly been located in a small number of regional locations, such as Europe and the USA. Only in the last couple of years have large-scale projects been built in India, China and, in 2013, South Africa. Japan and Latin America, notably Chile, are now in the large-scale project roll-out phase, supported in many instances by the modular power plant approach and adding to the geographical diversity.

Whatever direction incremental innovations in the modular power block approach may take, the platform is pushing ahead relentlessly and opening markets to utilities, investors and owners that were simply unimaginable only a few years ago.

> "It will be the downstream modular PV power plant that will drive the LCOE model past grid parity with fossil fuels."

The industry may have projected the expected roadmap to a lower cost per watt from the manufacturing floor, but it will be the downstream modular PV power plant that will drive the LCOE model past grid parity with fossil fuels and ensure global adoption of large-scale, unsubsidized electricity, regardless of technology type.

Modular PV power plants in practice

Hanwha Q CELLS: Q.MEGA

Outline: Hanwha Q CELLS' branded modular plant Q.MEGA is constructed in a 'cascade' format, incorporating 1.4MWp DC output blocks that include 24 modules per string and 6906 modules per block. A completed block can be independently grid connected.

Modules: Hanwha Q CELLS manufactures its own modules in Malaysia and Germany, which means that key components are always available. Options now include sourcing from Hanwha SolarOne, its sister manufacturer in China. Long-term yield security is achieved by Anti PID Technology1, Hot-Spot Protect and Traceable Quality Tra.QTM, as well as being VDE Quality Tested.

Inverters: 1 inverter station 1.3 MVA AC.

Special features: Continuous development of the modular system has led to high levels of optimization, with the benefit of construction times of 1MW per day, compared with 3.9 days for the system in 2009. This flexibility and high degree of system standardization helps keep costs low. The flexibility aspect also allows power blocks up to 3MW in size to be configured.

SunPower: Oasis Power Plant

Outline: The Oasis power block's high-efficiency modules are claimed to deliver higher output per square metre than conventional PV power plants, minimizing project footprint and permitting risk. Pre-engineered in 1.5MW power blocks, they are built with proven components to ensure reliability and lower risk to project investors. SunPower says it controls every step, from tracker and panel manufacturing to grid connectivity.

Modules: SunPower modules have been independently tested, with performance ratios of around 95%. The company launched the industry's first combined warranty that covers both power and product for 25 years.

Inverters: With advanced plant controls, the standardized Oasis inverter features voltage ride-through, curtailment control and dynamic power factor adjustment, enhancing grid interoperability for PV power plants.

Special features: The T0 Tracker with SunPower's 425W module maximizes the solar plant capacity factor and produces up to 30% more energy than fixed-tilt systems. The company also offers the C7 Tracker system, which combines single-axis tracking technology with rows of parabolic mirrors, reflecting light onto 22.8%-efficient 'Maxeon' solar cells.

First Solar: AC Power Block

Outline: First Solar integrates advanced technologies to optimize the entire power plant. The company has also recently developed PV tracking systems to capture more available sunlight.

Modules: First Solar manufactures its own CdTe thin-film modules with better temperature coefficient benefits than conventional c-Si modules.

Inverters: Advanced plant features include the ability to provide accurate energy forecasts, regulate voltage, curtail active power when necessary and react to changes in grid frequency. First Solar has used SMA Solar's utility-scale central inverters for several large-scale projects.

Special features: First Solar claims to have made significant improvements to BOS components in order to optimize the entire PV power plant and reduce life-cycle costs. It uses proprietary data acquisition, plant control and mounting systems to provide reliable and predictable solar energy, increased energy yields and system availabilities, and a lower LCOE.

BELECTRIC: 3.0 MegaWattBlock

Outline: BELECTRIC's new 3.0 MegaWattBlock is claimed to set new standards in solar power production and uses a maximum voltage of 1500V.

Modules: 3.0 MegaWattBlock is designed specifically to operate with First Solar's CdTe thin-film modules. BELECTRIC has also used CIS thin-film modules from Solar Frontier for the system.

Inverters: Developed in cooperation with GE and PADCON, the 1500V inverter system reduces system and maintenance costs. A material-saving design is also built with the highest levels of quality and provides superior surface area efficiency, according to the company. The turnkey system uses an efficient, grid-stabilizing power conditioning unit (PCU) with GE inverter technology, providing a claimed performance ratio of up to 85%.

Special features: The specially developed PCU includes an intelligent power plant controlling system, the inverter system and the transformer. The inverter system was optimized for the use of thin-film module technologies and is characterized by a high level of system efficiency.

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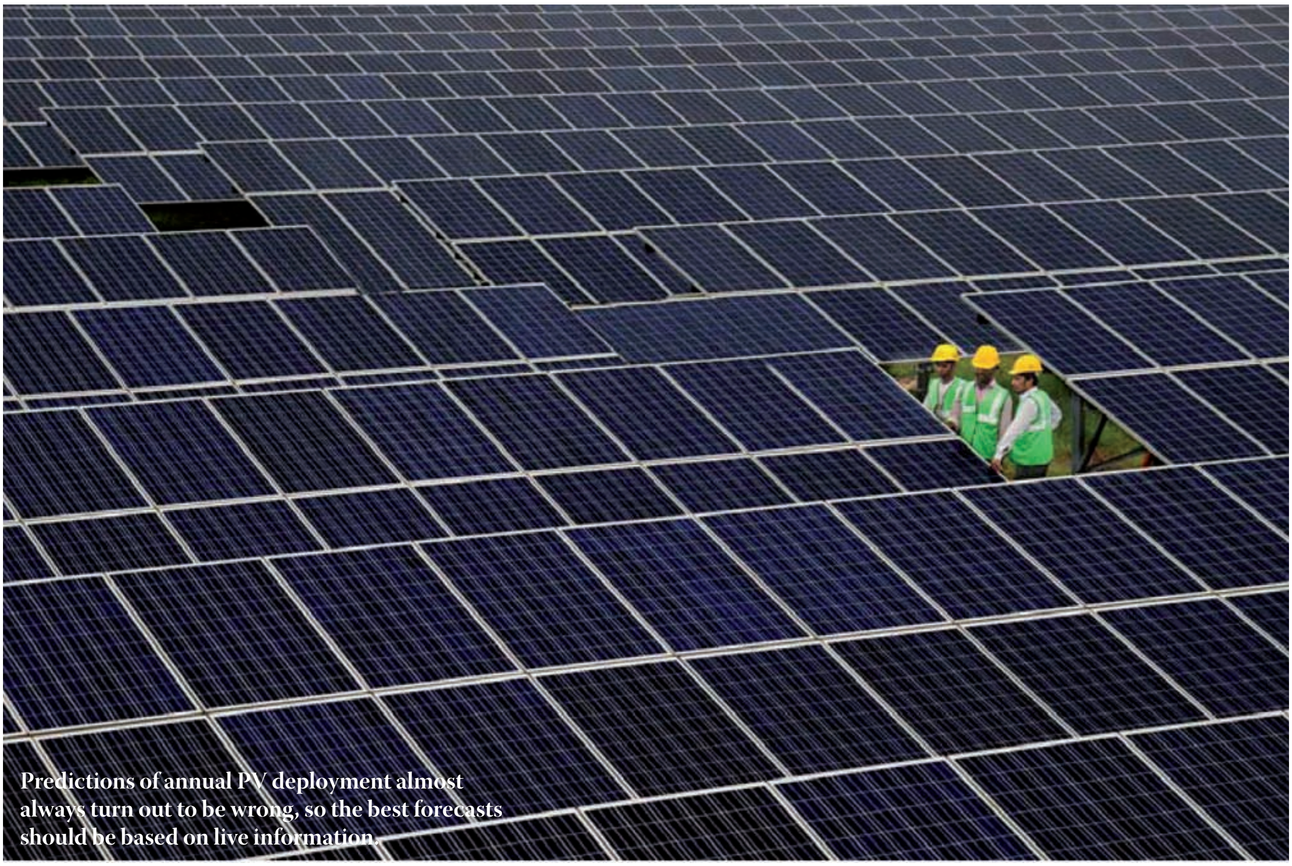
IHS: Why 2014 PV installation forecasts are all likely to be wrong



Source: Welspun Energy.

Predictions of annual PV deployment almost always turn out to be wrong, so the best forecasts should be based on live information.

Each year forecasts for how much new PV capacity will be added around the world are released. These are subsequently revised, updated, defended and invariably increased. The forecasts for 2014 from various banks and research firms, however, are quite different. The difference between the high-end and the low-end of expectations is massive – potentially 15GW – or put another way nearly half the amount installed in total the previous year.

Which forecast turns out to be "correct" is almost irrelevant – in fact I can almost guarantee that all of them will be wrong, including ours. Of course, one forecast will be closest to the final amount installed (if we can ever agree on even historical installations!), but right for the wrong reasons. The reason is that a forecast is made at a certain point in time based on known data and assumptions for factors that will impact on how the market develops in future.

These data and assumptions must of course change as time goes on. Does anyone really know what incentives, targets or laws the Chinese government will introduce in six months' time? Or what new trade cases will emerge and their outcome? Or if another natural disaster will cause a country to completely abandon its nuclear policy in favour of renewables? The answer of course to these questions is "no". Which is why all of the forecasts will undoubtedly be wrong.

However, the best forecasters will be able to deal with the huge list of variables, be constantly collecting new data and have people on the ground in the key markets to really predict – in real time – how the PV market will develop.

This is why the forecasts and models we use at IHS to predict solar demand are considered "live" and constantly changing based on the vast amounts of data that they rely on. Most changes are relatively minor, but some, such as when China's NEA increased its target from 12GW to 14GW for PV installations this year, can make a major impact – not just on total installations, but on the entire supply-demand balance. This announcement, which was made on 13 January – after the majority of the forecasts and predictions were made – just illustrates why most market forecasters will all likely be wrong.

But given most forecasts for 2014 were made at roughly the same time, why do they vary so massively? Here's a few of the reasons:

1. We're measuring different things

In the 14 years I've been researching various markets, I've never come across another industry like PV where researchers can't even broadly agree on what happened in the past. One of the reasons is that what they're in fact measuring (whether they know it or not) is different. Many researchers rely on secondary data or government statistics and these tend to measure different metrics. For example, IHS uses DC capacity for PV systems installed in a given year, including off-grid systems. Government statistics and other researchers often use AC-output, grid-connections or approvals (rather than installations) and sometimes a mixture of all of these. Given this, it's easy to see why market researchers rarely agree on the size of the PV industry.

2. China

China is one of the biggest variables in terms of both how many PV panels will get installed this year, but also what will happen to the entire supply chain as its government chooses to continue or revoke support for many of its ailing suppliers. China is also where most researchers disagree and also one of the biggest variables in our forecast. It could install potentially as much as 14GW this year, or as 'little' as 10GW. The recent NEA announcement to increase its target for ground-mount projects and slightly deemphasise the dependence on distributed PV has indeed caused IHS to raise its forecast for this country.

3. Other 'upside' potential and risks

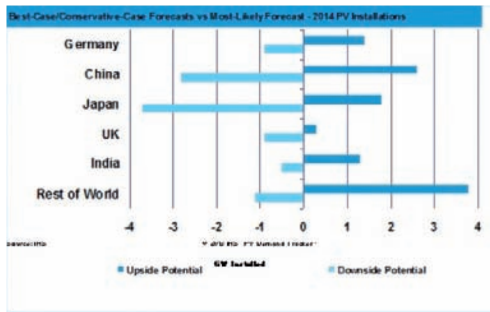
Other key markets could of course install more than IHS has predicted, but equally present inherent risk. Japan is a great example of this and in late 2012 we first warned of the potential of a boom-bust cycle happening here. Whilst we expect just over 7GW to be installed in Japan this year, we also recognize this could be as high as 9GW. Given that it will likely be the second largest market globally again this year, the risks presented in this country are somewhat worrying. Its residential feed-in tariff, which is due to cease at the end of Q1, is unlikely to be renewed. This risk is further compounded by an ongoing review of the "mega-solar" pipeline and possible cancellation of permits.

Other European markets also offer upside. The UK, for example, which is now rather driven by ground-mount projects installed under the Renewable Obligation Certificate scheme, has the potential to install more than 2GW in 2014. But despite strong government support for solar and renewables, the quest for cheap shale gas as enjoyed by the US, the escalating electricity prices suffered by consumers and industry and the ongoing uncertainty over the European Union's mandatory renewable energy targets creates further risk to Europe's PV market. Even in Germany, the support for renewables continues to wane, as the government seeks to confine soaring electricity cost and the impact on the competitiveness of the German economy.

4. Emerging markets

The pace at which emerging PV markets will develop is another topic that most researchers seem to constantly disagree on. The main reason is that some expect emerging markets to behave in a similar way to 'established' markets that rely heavily on incentives and subsidies, like Germany or Japan. Instead of being fluid and rapid to expand soon after PV policy is announced and introduced, emerging markets develop in a much slower fashion.

The announcement of a multi-gigawatt pipeline does not mean we'll see a new gigawatt-scale market emerge in a single year.



IHS 2014 PV market forecast highlighting upside and downside to forecast projections.

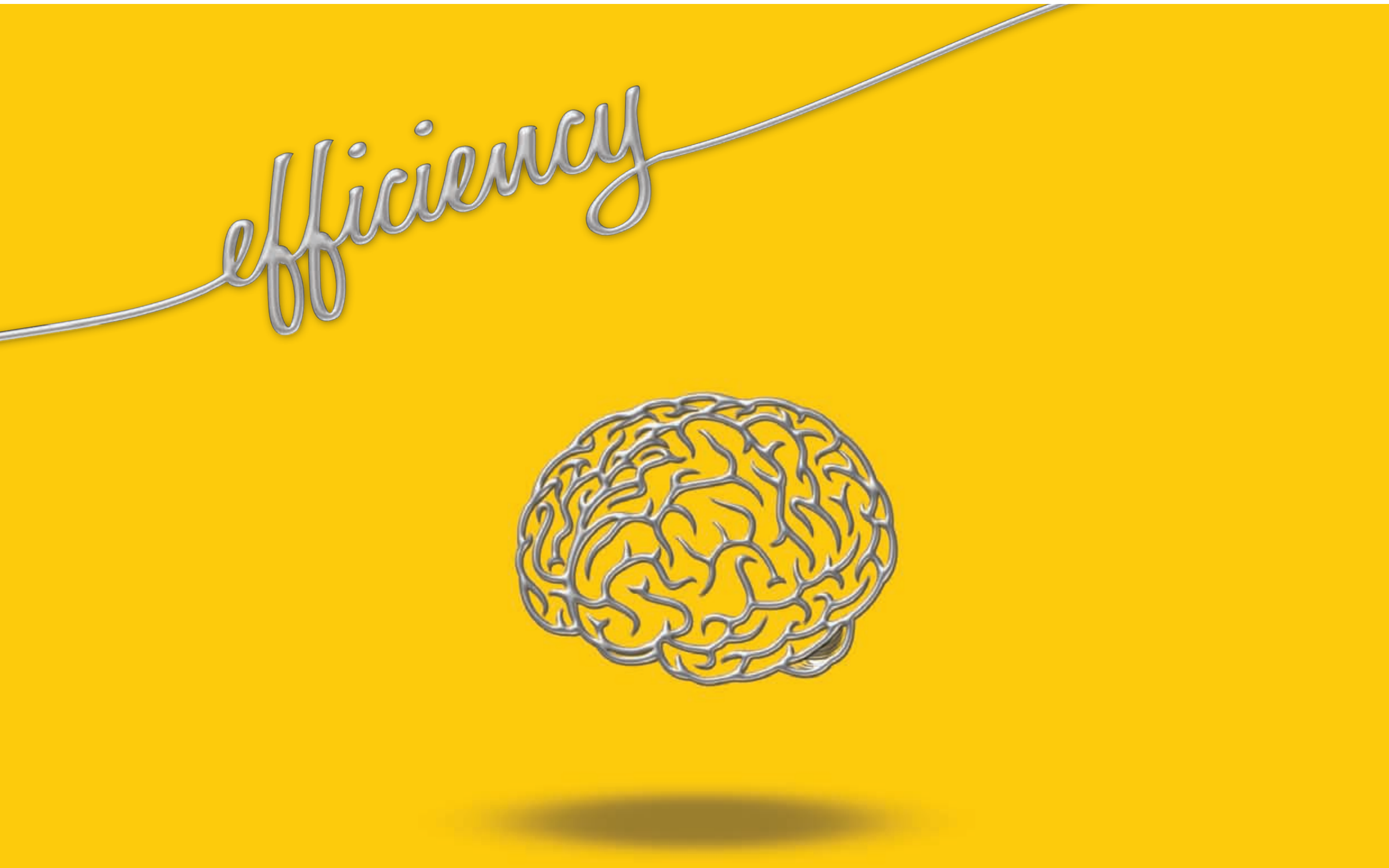
Often these markets do not rely on a direct subsidy but instead are based on PPAs. You just need to look at Chile to understand this point. Chile's multi-gigawatt PV pipeline has been publicized since 2012 with many of the projects approved by regulators. Despite this, little over 100MW had been installed in Chile by the end of 2013. The main reason behind this is that despite the gigawatts of projects being 'approved,' they lacked an off-taker of the power – no-one had agreed to buy the electricity these plants would produce. Most of these emerging markets that we track on a daily basis do not force utilities to purchase PV electricity at a fixed price, this is one key reason why they will develop differently to subsidised markets.

The markets also require PV to compete on a more or less level playing field with other sources and renewable energy technologies. Brazil is a great example. Whilst viewed very positively as most as a major PV market, not a single PV project was selected – as predicted by IHS – in the recent national bidding process due to extremely low prices that were achievable from equivalent wind projects. That's not to say this won't change, and indeed we expect hundreds of megawatts to be installed in Brazil, but it illustrates how an overly aggressive view on how quickly emerging markets will develop can impact the ability to forecast global demand accurately.

Adding all of these variables together its fairly easy to see why that whilst our December 2013 "base-case" scenario would see around 41GW installed in 2014, our "best-case" is more than 53GW. However, equally the risks to the PV market's development remain clear and I'm certain that further factors will arise that mean that most forecasts and predictions will be revised as the year goes on. Being able to track all of these developments in real time in dozens of markets globally whilst also assessing PV's role in the wider energy mix, particularly in non-subsidised markets, will be key to being a successful forecaster for this industry, and of course much more valuable and important than being able to formulate the highest growth projection.

This is an edited version of a blog that originally appeared on PV-Tech.org.

Ash Sharma is senior director of research at analyst firm IHS.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