Nineteenth Edition

Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS

Wright Williams & Kelly: PV technology areas for largest near-term paybacks
imec: industrial version of PERC technology, yielding cell efficiencies beyond 20%
Helmholtz-Zentrum Berlin: discussion of alternatives to CdS buffer layers in CIGS
PI-Berlin: PID and its correlation with experience in the field
Sandia National Laboratories: PV plant optimization

First Quarter, February 2013

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Cover image shows Ni electroplating reducing Ag consumption by up to 50% and a key enabling technology for Cu metallization

Image: InCellPlate® series, courtesy RENA GmbH

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Foreword

Last year, 2012, was extremely difficult for the solar industry as the increasing overcapacity issues for manufacturing forced some companies to merge or to exit the market completely. Margins shrank along the supply chain and aggressive expansion plans from Chinese manufacturers have been put on hold while the market recalibrates itself.

The numbers for deployment are in and show that PV demand in 2012 reached 29GW, up 5% from 27.7GW in 2011. Emerging markets such as India and South America were not able to make up for the steady drop in European demand, driven primarily by Italy.

So for manufacturers who had their heads in the bunker during 2012, fighting falling ASPs and eroding margins, what lies in store for this coming year?

The good news is that the tariffs imposed on Chinese imports haven't had that big an effect on the US market, with almost 3.6GW installed — a larger sum than anticipated by the Solar Energy Industries Association at the beginning of 2012. In December 2012, polysilicon prices actually increased (almost 7%) for the first time in 18 months and module prices in Europe stabilized in Q4 of 2012. End-user demand from the Japanese market is driving utilization rates above 70% in top-tier Chinese module manufacturers.

Best-practice manufacturers are investing in new technology that will help them reduce costs and increase margins. As a result, research and development budgets are up and supplier panels for materials and gases are being rationalized to look for the best possible partners. In *Photovoltaics International*, we are continually committed to giving you, the engineer, the best possible technical information to help you make informed purchasing decisions, driving your margins up.

Wright Williams & Kelly (p.12) return in this issue with their popular analysis of payback on technology buys; crucially they analyze n-type wafers, Al_2O_3 passivation and copper metallization. SERIS (p.51) shows us how to achieve 18.7% efficiencies using low-cost etching techniques on diffused wafers.

We also have two important technology roundups: CIGS (p.63) from Helmholtz Berlin, and PV module encapsulation techniques (p.81) from Fraunhofer ISE.

In 2013 we here at *Photovoltaics International* remain committed to bringing you the very best technology articles in the world and look forward to working with you this year.

Sincerely,

David Owen
Publisher
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:

Gary Yu, Senior Vice President, Operations

Mr. Yu served as Trina Solar's Vice President of Manufacturing since May 2007 and in July 2010 was promoted to the position of Senior Vice President of Operations. Mr. Yu has 17 years' manufacturing management experience in semiconductor-related industries. Before joining Trina Solar, he was Managing Director of Wuxi Lite-On Technology, an LED assembly company based in China. Prior to Wuxi Lite-On Technology, he served as a Director of Manufacturing for 1st Silicon Sdn. Bhd. in Malaysia, prior to which he worked at Macronix International, a semiconductor integrated device manufacturer in Taiwan. Mr. Yu has a master's degree in Industrial Engineering and Management from National Chiao Tung University in Taiwan and a bachelor's degree in Chemical Engineering from Tunghai University.

Takashi Tomita, Senior Executive Fellow, Sharp Solar

Takashi Tomita has been working at Sharp for 34 years and is widely recognised as a fore-father of the solar industry in Japan. He was responsible for setting up Sharp's solar cell manufacturing facilities in Nara and silicon production in Toyama. Takashi's passion for solar power has led him to hold numerous posts outside of his roles at Sharp, including: Vice Representative at the Japan Photovoltaic Industry Association; Committee Member of Renewable Energy Portfolio Standard of METI; Adviser Board Member of Advanced Technology of Nara; Visiting Professor of Tohoku University; Adviser of ASUKA DBJ Partners (JAPAN) and Adviser of Global Catalyst Partners (US).

Dr. Peng Heng Chang, CEO, Motech Industries, Inc.

Dr. P.H. Chang was elected CEO of Motech in March 2010. Dr. Chang has over 30 years of experience in management at multinational technology companies and in-depth knowledge in Materials Engineering. Prior to joining Motech, Dr. Chang was VP of Materials Management and Risk Management, VP of Human Resources and Senior Director of Materials Management at Taiwan Semiconductor Manufacturing Co. (TSMC); VP of Administration at Worldwide Semiconductor Manufacturing Co. and Professor of Materials Science and Engineering at National Chiao Tung University in Hsinchu, Taiwan. Dr. Chang also worked for Inland Steel Co. and Texas Instruments in the US prior to 1990. He received his Ph.D. degree in materials engineering from Purdue University in 1981.

Professor Eicke R. Weber, Director of the Fraunhofer Institute for Solar Energy Systems ISE in Freiburg

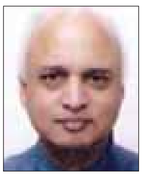
Professor Eicke R. Weber is the Director of the Fraunhofer Institute for Solar Energy Systems ISE in Freiburg. Weber has earned an international reputation as a materials researcher for defects in silicon and III-V semiconductors such as gallium arsenide and gallium nitride. He spent 23 years in the U.S. in research roles, most recently as Professor at the University of California in Berkeley. Weber is also the Chair of Applied Physics, Solar Energy, at the University of Freiburg, and during his career has been the recipient of several prestigious awards including the Alexander von Humboldt Prize in 1994, and the German Cross of Merit on ribbon in June 2006.

Dr. Zhengrong Shi, Executive Chairman and Chief Strategy Officer, Suntech

Dr. Zhengrong Shi is founder, CEO and Chairman of the board of directors of Suntech. Prior to founding Suntech in 2001, he was a Research Director and Executive Director of Pacific Solar Pty., Ltd., the next-generation thin-film technology company, before which he was a Senior Research Scientist and leader of the Thin Film Solar Cells Research Group in the Centre of Excellence for Photovoltaic Engineering at the University of New South Wales in Australia. Dr. Shi holds 11 patents in PV technologies and is a much-published author in the industry. His work has earned him such accolades as "Hero of the Environment" (TIME magazine 2007) and "Corporate Citizen of the Year" at the China Business Leaders Awards 2007. A member of the NYSE advisory board, Dr. Shi has a Bachelor's degree in optical science, a Master's degree in laser physics and a Ph.D. in electrical engineering.

Dr. Sam Hong, President and COO of Neo Solar Power

Dr. Hong has more than 30 years of experience working in the solar energy industry. He has served as the Research Division Director of Photovoltaic Solar Energy Division at Industry Technology Research Institute (ITRI), a research organization that serves to strengthen the technological competitiveness of Taiwan, and Vice President and Plant Director of Sinonar Amorphous Silicon Solar Cell Co., which is the first amorphous silicon manufacturer in Taiwan. In addition, Dr. Hong was responsible for Power Subsystem of ROCSAT 1 for the Taiwan National Space Program. Dr. Hong has published three books and 38 journal and international conference papers, and is a holder of seven patents. Dr. Hong was the recipient of Outstanding Achievement Award from the Ministry of Economic Affairs, Taiwan, and was recently elected as chairman of the Taiwan Photovoltaic Industry Association.



Dr. G. Rajeswaran, President and CTO of Moser Baer Photovoltaic Ltd

Raj served as President and CTO of Moser Baer Photovoltaic Ltd. from July 2007 until October 2008, since which time he has been Group CTO for all the Moser Baer business units and holder of the CEO function for launching new businesses. He spent 22 years with Eastman Kodak Company as the Vice President of Advanced Development & Strategic Initiatives, where he managed Kodak's Japan display operations including technology & business development in Japan, Taiwan, Korea and China. He has also served as Vice President and on the board of SK Display Corporation, and worked in technology development with Brookhaven National Laboratory. Raj has a Ph.D., an M.Tech. and a B.E. in electrical engineering. A much-published author, speaker and patent holder, Raj is a member of the Society for Information Display (SID) and has chaired several international conferences in the field of OLEDs.

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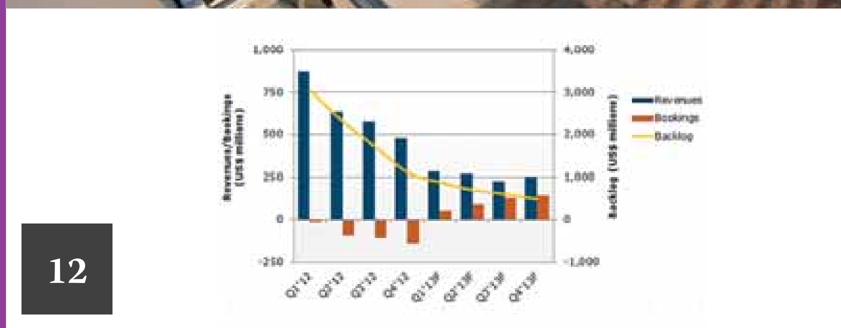
Fab & Facilities



News

Over 350 small Chinese solar companies stopped operating in 2012

ASP declines in 2012, driven by industry overcapacity throughout the PV supply chain, forced over 350 companies in China, from equipment suppliers and polysilicon producers to module manufacturers, to stop operations entirely. A significant influx of new entrants in 2011 led to the number of Chinese manufacturing companies directly involved in the PV industry increasing from 807 to 901. However, in 2012 the number of companies exiting the sector due primarily to bankruptcy was close to 300, reducing the number of players to 704. During 2012 the number of core solar chain manufacturers dropped from 901 to 704, with a particular drop among panel manufacturers from 624 manufacturers to 454 manufacturers. In addition a further 180 core chain manufacturers left the market, meaning that there are now only 524 currently operating manufacturers, a 42% decline since 2011.

Source: news.investers.com

Over 350 companies in China have been forced to stop operations entirely.

Capacity Expansion News Focus

1366 Technologies opens 25MW wafer factory

US solar manufacturer 1366 Technologies has opened its new 25MW wafer manufacturing plant in Bedford, Massachusetts. The facility is expected to employ 100 people in the commercial production of the company's Direct Wafer technology.

The company claims the technology represents a "transformative manufacturing process" that produces wafers at half the normal cost. The plant is the first of two planned by the company.

Kyocera's European solar module plant at full capacity

Increased demand from Japan following the introduction of a new feed-in tariff last year and conservative capacity

Source: Kyocera

Kyocera's module assembly plant in the Czech Republic is now operating at full capacity.


Source: Stion

Stion has secured around US$25 million to facilitate expansionist plans.

expansions over several years mean that Kyocera's module assembly plant in the Czech Republic is now operating at full capacity, the company has revealed. Strong demand caused by high tariff rates and a renewed focus on the Japanese market by all domestic module producers has been a welcome boost, especially considering waning European markets and highly competitive prices which hit Japanese producers hard. The company hinted that further expansion of capacity at the plant would be necessary, yet did not provide further details.

Applied Nanotech and YHCC open 1,000 ton capacity PV metallic inks plant in China

Materials IP developer, Applied Nanotech has opened a proprietary PV metallic inks and paste production plant in China with JV partner Sichuan Anxian Yinhe Constructional & Chemical Group (YHCC), an electronic paste manufacturer focused on the PV industry. The materials manufacturing plant is said to be operated by Yinhe Starsource Technology, a subsidiary of YHCC and has a volume capacity of over 1,000 tons of aluminium and silver inks and pastes per annum.

Stion obtains US$25 million to expand production

Stion, a thin-film manufacturer headquartered in California, has secured around US$25 million to support its plans to expand its production facility, media reports reveal. Stion's Senior Director of Business Development Frank Yang said that the majority of the company's existing investors were participating in the financing which was led by Khosla Ventures. The funding will be used to increase the production capacity at Stion's facility in Hattiesburg, Mississippi, from 100MW to 140MW a year.

Module production begins at Panasonic's Malaysia plant

Panasonic has begun production at its new 300MW module manufacturing facility in Malaysia. The plant is Panasonic's first integrated manufacturing facility, producing wafers, cells and modules under one roof. It will manufacture Panasonic's HIT solar modules, boosting the company's overall module output by 50% to 900MW annually.

However, the company has already confirmed that it will be indefinitely shelving its plans to expand the Malaysian plant to 1.5GW due to the global slowdown in the solar industry and a 5% decline in its sales.

Astana Solar opens PV module plant in Kazakhstan

Module manufacturing start-up Astana Solar has started ramping its newly completed 100MW assembly plant in the Republic of Kazakhstan. A subsidiary of NAC Kazatomprom JSC, one of the worlds largest uranium-mining companyies, Astana Solar has already received supply contracts for its modules from uranium mining firm KATCO, which is a joint venture business between France-based AREVA and Kazakhstan-based Kazatomprom, both nuclear power providers. The KazPV project is part of a partnership signed between Kazakhstan and France in October 2010 and includes technology supplied from French business.

China Sunergy establishes production facility in Turkey

PV manufacturer China Sunergy has established a new manufacturing facility in Istanbul, Turkey, with its local partner Seul Energy Investment Corp, PV systems

Source: China Sunergy

China Sunergy has established a new manufacturing facility in Istanbul, Turkey.

provider and installer in Turkey. Under CSUN Eurasia, they will manufacture PV cells and PV modules in Turkey and invest in downstream solar projects in Turkey and its neighbouring countries. The production plant covers 22,000 square metres and is located in the Trade Free Zone in Istanbul. It has a 150MW PV module line installed and will become operational in January. The companies are also installing a 100MW solar cell line which is scheduled to begin producing solar cells in March.

Wacker ramping polysilicon production and ending short-time work due to demand

In a rapid turnaround from last year, Wacker Chemie has stopped short-time working schedules at its Burghausen polysilicon plants and will ramp capacity utilisation rates due to renewed demand. Wacker said it has sold more polysilicon in January than previously expected and recent new order intake was in excess of either inventory or current utilisation levels to meet demand. The company had reduced production utilisation rates to 80% of nameplate capacity in the third quarter of 2012 due to weak demand. Wacker noted that utilisation rates in the fourth quarter were lowered further to "to two-thirds of full utilisation."

centrotherm wins follow-on solar cell line key equipment deal with CECEP

Having previously supplied PECVD and diffusion furnaces to China-based PV module manufacturer, CECEP Solar Energy Technology in 2010, as it ramped its first production lines, centrotherm photovoltaics has received a major follow-on order.

CECEP, which like many companies had aggressive plans to ramp c-Si module capacity beyond 1GW as rapidly as possible, has selected centrotherm to provide anti-reflective coating and phosphorous diffusion systems as part of its next phase expansion. CECEP was said to have had an initial capacity of 180MW, while centrotherm's new order will support 300MW of annual production. CECEP opened tenders for the expansion in August 2012, according to centrotherm.

KKR acquires Canada's second largest PV plant

Private equity giant KKR acquired the second largest PV facility in Canada in its first solar investment from a US$1 billion infrastructure fund in February. It has further confirmed it is "open" to owning similar assets. The global investment firm, with US$77.5 billion in assets under management, acquired three solar PV energy projects from SSM Projects, an affiliate of Starwood Energy Group, which has developed projects in Ontario with a combined capacity of 69MW. To date, KKR's Global Infrastructure Fund has made seven investments, four of them in the renewable energy space, three of those in solar and one in wind.

Cencorp to open PV factory in Finland

Finnish company, Cencorp, has announced that it plans to set up a photovoltaic module factory in Mikkeli, Finland. Cencorp purchased Sunweb Solar Holdings for a reported €450,000 (US$616,000) in cash and €550,000 worth of Cencorp shares, scheduled to be ready in early 2014.

Proinso opens branch in Japan

Solar suppliers Proinso has extended its PV modules operation in Japan by opening a new branch in Tokyo.

The company said the new branch formed part of its strategy to focus on new international markets, with at least 88% its income is generated from international sales through its network of branches in Japan, Greece, Italy, US, UK, Spain, Canada, China, Australia, India and Thailand.

Solar Shakeout

Iatso files for insolvency

Spanish photovoltaic panels producer Innovacion en Alta Tecnologia Solar (Iatso) has filed for insolvency. The company fell victim to tough trading conditions, which included Spain's recent reduction of renewable energy premiums. Spanish manufacturers have also had to tighten their belts in the face of a deteriorating domestic market and stiff competition from Asian companies. Iatso is the second Valencia-based photovoltaic panels producer to have filed for insolvency, following Siliken.

SiC Processing warns creditors to expect low debt recovery

Slurry recycling specialist, SiC Processing which is currently in receivership, has warned unsecured creditors to expect low debt recovery due to a preliminary, unaudited assessment of its assets. The company said the valuation of the company had been impacted by the state of the sector and the impact the market conditions were having on its customer base.

PV Crystalox to undertake radical restructuring

UK-based solar wafer producer, PV Crystalox Solar will implement a significant reduction in its workforce, while discontinuing its polysilicon operations and wafer production in Germany and heavily cutting ingot production in the UK. The struggling company had previously halted polysilicon production and cut wafering operations with job losses as it faced significant ASP declines for its products due to chronic overcapacity on polysilicon and solar wafers. The company had been operating for most of the year with very low utilization rates for its wafering operations. PV Crystalox had warned in its half-year financial report that management would undertake a strategic review of the business with the possibility that it would wind-down all operations and return cash to investors.

Hemlock reducing workforce and polysilicon capacity; delays ramp of new production facility

Major polysilicon producer Hemlock Semiconductor has cited unresolved trade disputes, notably with China, as a key factor behind the decision to lay off approximately 400 employees, while reducing polysilicon production and delaying the ramp of its new plant in Tennessee.

Hemlock said that lay offs would affect 300 employees at its Tennessee site, which has yet to be commissioned and start production and 100 jobs would be lost at its major production site in Michigan.

The company plans to reduce production capacity, though did not provide details regarding metric ton quantities. Hemlock was on target to boost production to around 46,000MT per annum, up from 12,300MT in 2008. The new plant was to come on stream in 2013.

Hemlock said that the Tennessee site was effectively being put on hold, pending market conditions and the resolution of the trade disputes.

Global Solar cuts workforce by 70%

Struggling flexible CIGS thin-film firm, Global Solar Energy said it had reduced its workforce by 70% as it continues to seek a buyer. Key production and technical staff as well as management have been retained. The majority of employees impacted by the job losses have come from its roofing product line. Production has been curtailed but continues for previously contracted orders.

Siemens-based polysilicon production at REC uneconomical

Renewable Energy Corporation ASA (REC) is to stop production of Siemens-based solar grade polysilicon at its Polysilicon I facility in Moses Lake, Washington State, US. The company said that current price declines due to severe overcapacity in the sector and ongoing weak demand meant that market prices were below production costs. The closure of the facility will potentially result in the loss of 46 jobs at the site. REC said it would try and find positions at other plants. Production at REC's Polysilicon I facility was said to be 2,400 MT per annum.

Source: REC Solar

REC said that current market conditions meant that market prices were below production costs.

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When capacity buys are not an option: Technical trends in c-Si cell manufacturing and their implications

David Jimenez & **Alan Levine**, Wright Williams & Kelly, Inc., Pleasanton, California, USA

ABSTRACT

Economics will always play a crucial role in the way PV technology advances. However, the current generation of products is facing substantial business challenges in the attempt to scale the product technologies. This paper is the fifth in a series covering business analysis for PV processes. The methods applied in these papers fall into two categories: cost of ownership (COO) modelling and cost and resource modelling. Both methods examine the business considerations associated with the adoption of new processes, tools or materials. This is more critical than ever. Near-term issues – in some cases the survival of the business – heavily influence today's decision processes. This paper tries to identify the areas that it is thought will produce the largest near-term paybacks. The areas identified are n-type wafers, Al_2O_3 passivation and copper metallization.

Solar cell production outlined

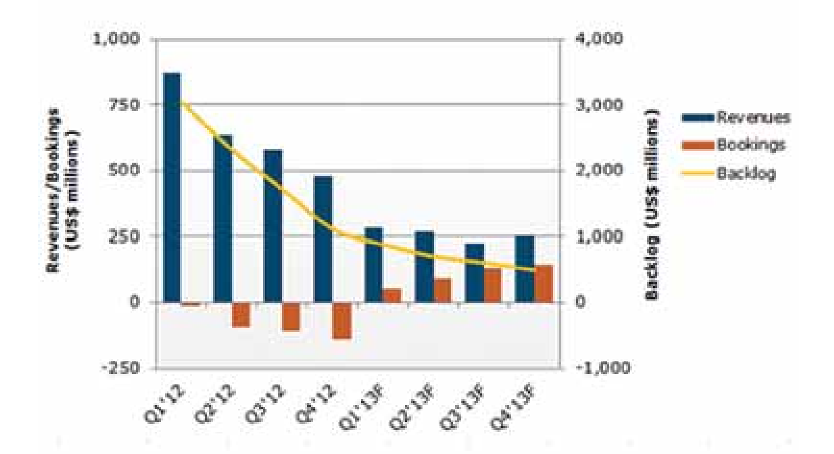
Any discussion of technical changes to any steps in crystal silicon (c-Si) PV manufacturing must take into consideration the entire solar cell production flow. Therefore, before the processes of interest are described, it is worth first outlining the baseline process through which the silicon wafer travels on its way to becoming a fully-fledged solar cell.

The silicon wafer is sliced from a monocrystalline or multicrystalline silicon ingot. This step can be carried out either directly at the silicon foundry or by the solar cell manufacturer. The sliced wafer then goes through several distinct manufacturing steps, after which it is ready for mounting into a solar panel.

The first step in the cell manufacturing cycle is wet etching, which is described in depth in the second paper in this series [1]. Here, the imperfections created in the sawing process are removed, after which the wafer's surface is texturized to create the microscopic pyramid structures that will enable it to trap sunlight rather than reflecting it.

Described in the first paper in this series [2], the second step is a thermal diffusion process whereby an n-type layer is diffused through the wafer's top layer and down into its structure. Typically made of phosphorus-rich material, this n-type layer combines with the wafer's own p-type material to create the cell's p-n junction, a planar semiconductor device that will generate electrical current. During the diffusion process, a layer of glass is created on the surface of the cell and is removed in an additional etching and de-glassing process.

In the third step, the cell's antireflective (AR) layer is laid down in a plasma-enhanced chemical vapour deposition (PECVD) process that gives the cell its blue colour, after which the cell is ready for metallization. This was described in detail in the third paper in this series [3]. The PV industry uses screen printing as the method of choice for depositing silver and aluminium onto its solar cells.



Credit: NPD Solarbuzz

Figure 1. Forecast PV-specific metrics for the top 10 PV equipment suppliers.

Market trends

Solar PV equipment spending was US$3.6 billion for 2012, down from US$12.9 billion in 2011, according to new research in the latest NPD Solarbuzz PV Equipment Quarterly report. Covering c-Si from ingot to module and thin film, the report says spending for 2013 could drop to levels not seen in the industry since 2006. "Spending for 2013 is forecast to decline even further to US$2.2 billion," said Finlay Colville, Vice-President of NPD Solarbuzz. The market analyst group expects only eight PV equipment suppliers to have PV-specific revenues during 2012 in excess of US$100 million, compared to twenty-three in 2011.

"Excessive investment in 2010 and 2011 was the catalyst of the over-capacity and over-supply situation that exists today. It was also a key factor in end-market price erosion that forced many of their customers to file for insolvency. The days of PV-specific backlogs and revenues at the billion-dollar level are unlikely to be repeated for at least three years," stated Colville.

With so much competitive c-Si capacity shipped during 2011 and 2012, NPD Solarbuzz states that the biggest fear for tool suppliers is the emergence of a secondary equipment market across China and Taiwan. Most importantly, this would delay any upturn in equipment spending.

> "The biggest fear for tool suppliers is the emergence of a secondary equipment market across China and Taiwan."

With regard to module shipments and revenues, IHS iSupply is expecting overall global installation markets to pick up again after the first six months of 2013 and then continue to improve over the rest of the year. Meanwhile, overcapacity that had built up because of massive investments in 2010 and 2011 will have less dramatic repercussions in 2013 than in 2012.

The IHS report said the decline in PV module prices afflicting the market will slow down in 2013 and then eventually stop by the second half of the year. By the fourth quarter of 2013, average crystalline module prices are forecast to reach US$0.55 per watt, down 14% from the same time in 2012, compared to a bigger contraction of 32% between the fourth quarter of 2011 and 2012. Overcapacity and a decline in pricing, as well as slowing growth in key worldwide markets, will serve to keep the global PV market for solar modules depressed, with recovery not expected until well into the second half of 2013. While this sounds better than the scenario for equipment suppliers, double-digit price erosion is not something that the market can sustain indefinitely.

This is not a rosy picture for the PV market, or its supply chain, and one of the conclusions is that, for many, it may never be so again. Why? The larger macroeconomic environment has changed. To a large degree, PV remains dependent on favourable government policies (subsidies, feed-in tariffs, carbon taxes, etc.). These policies are struggling to gain (or maintain) traction as governments (e.g. USA, Spain, Italy) struggle with massive budget deficits and accumulated debt. Separately, the widespread use of hydraulic fracturing has reduced the price of natural gas (a competing source of electricity generation) by a factor of three. Further, the natural gas supply chains are extremely well capitalized, involving some of the largest and most profitable corporations in the world.

In short, there is an oversupply of product, a substantial risk on the demand side due to financial constraints with governments, and a competitive technology (natural gas) that has undergone substantial and sustainable cost reductions.

What does this mean going forward? The bar has been raised. It is tempting to compare the solar industry with the semiconductor industry, where boom and bust cycles are common. However, the boom–bust cycles in the semiconductor industry have almost always been traced to basic supply and demand. It has been decades since that industry was highly dependent on government policy, and most of the competition has come from within the integrated circuit (IC) industry, not from competing technologies outside the industry.

One clear reality – there is no more room for current-generation 'me too' PV roadmaps. Current 'me too' products are unlikely to be profitable for a long time, if ever. With double-digit price erosion for c-Si modules, manufacturers must look for competitive advantages and those cannot be had with older, off-the-shelf processes. Upgrading processes is the only potentially viable business plan. In practice, companies should get accustomed to continuous upgrading; a static solar cell factory will not remain competitive for long, now or at any time in the foreseeable future. Just to be clear, the market will punish those who do nothing to improve their processes. As hard as it is to invest in a down cycle, it is the only way to survive.

> "Upgrading processes is the only potentially viable business plan."

Does that mean the end of 'turnkey factory sales'? The authors think that is a likely outcome. Additionally, module manufacturers are acquiring unique technologies at the cell level to ensure their survival through sustainable competitive advantages. As a result, it is expected there will be several announcements involving a deeper level of partnering (probably including acquisitions) of novel cell manufacturers and intellectual property (IP) developers before their technologies have been released to the broader market.

Technology upgrades

The question then becomes, given the current challenges, where does one look for these technology developments that have the potential to create competitive advantages? This section looks at the best guesses for short-term opportunities – those that can begin to make an impact within 12 months, as well as other potential areas of interest. This section concludes by looking at one 'up-and-coming' approach to achieving improvements in cell efficiency and reductions in cell manufacturing costs.

N-type wafers [4]

An early driver of PV was satellites. P-type (boron-doped) cells (i.e. cells based on p-type wafers) proved to be less sensitive to degradation caused by exposure to cosmic rays than n-type cells. This early application drove p-type cell development and that is where most production remains today. Recent research suggests a likely move to n-type (phosphorus-doped) cells. The results have shown a potential to outperform p-type cells in terms of efficiency. According to the International Technology Roadmap for Photovoltaics (ITRPV 03/2012), the market share of n-type cells could reach approximately 30% of the monocrystalline silicon solar module market by 2015 (currently around 5%).

An advantage of n-type cells is that they do not suffer from the light-induced degradation (LID) seen in p-type cells. In addition, n-type cells are less sensitive to impurities that are typically present in silicon feedstock. Consequently, n-type cells with higher efficiencies can theoretically be produced at a lower cost than p-type cells using the same wafer-manufacturing methods (Czochralski crystal pulling). N-type wafers, however, show a larger distribution of electrical resistance. This leads to a reduction in the number of wafers obtained from an ingot. One proposed solution is to use a continuous-feed Czochralski puller, which would provide equipment companies with new sales opportunities.

Al_2O_3 passivation [5]

Al_2O_3 is of increasing interest because of the promise it holds for providing excellent passivation of p-type c-Si surfaces on industrially feasible scales. While Al_2O_3 exists in different crystalline forms, amorphous Al_2O_3 films are used for passivation layers. The films are transparent over the wavelength region of interest for solar cells. Al_2O_3 films for c-Si surface passivation can be deposited by atomic layer deposition (ALD) and PECVD, as well as by physical vapour deposition (PVD) sputtering. Sol-gel processes have also been investigated. Annealing of the films is typically required to achieve a high level of surface passivation. Results of Al_2O_3 with n-type cells have shown efficiencies greater than 23%.

PECVD and PVD are certainly scalable in c-Si PV manufacturing. The competitive edge of existing PECVD systems is that they can easily be modified to avoid large investments in new technologies. The results reported for PVD have not been as good as for PECVD and ALD. Conventional ALD is unsuitable for high-throughput solar cell production. However, throughput can be addressed by batch processing or through spatial-ALD (based on spatial separation of precursor gases instead of time-based separation), which would allow in-line atmospheric processing.

With regard to cost, it has been reported that the deposition of Al_2O_3 can be accomplished for just a few cents per cell. However, the implementation of rear-surface passivation schemes can have a major impact on cost of ownership (COO). One important cost-related finding is that passivation using Al_2O_3 does not require a semiconductor-grade precursor, and that solar-grade $Al(CH_3)_3$ produces excellent results, as does using less pyrophoric precursors.

Cu metallization [6]

The metallization of c-Si cells is one of the main cost drivers in the manufacturing process [3]. Screen printing of silver pastes is still the dominant technique, but the need to replace silver with copper in order to lower costs is widely acknowledged. While elemental silver has better conductivity than elemental copper, electroplated copper has superior conductivity when compared with current silver pastes: data indicate up to a 0.5% cell efficiency improvement with electroplated copper.

Using copper as an electrode material for c-Si cells presents a number of issues that need to be addressed. First, copper diffuses into the silicon, where it forms a trap for the charge carriers in the semiconducting material: consequently, a diffusion barrier is required. Second, copper (unlike silver) oxidizes into a porous compound when exposed to air; addressing this issue requires extra protection of the electrode contact (e.g. capping). Third, the use of copper as an electrode material increases the complexity of the solar cell manufacturing process. For example, in order to make contact with the silicon wafer, the silicon nitride passivation layer must be opened by either etching or laser ablation. Subsequently, a diffusion barrier must be deposited followed by copper deposition. The latter can be done by electroplating, a technique that is well known in the IC industry, albeit at throughputs far below the requirements for solar manufacturing.

Additional paths

There are many possible approaches to achieving improved cell efficiency and, hopefully, lower manufacturing costs (cost/watt), resulting in subsequent reductions in cost for the end user (levelized cost of electricity – LCOE) and in total cost of ownership for energy (TCOe). While the previously mentioned approaches, in the authors' opinions, have the best chances of impacting manufacturing during the next 12 months, there are other approaches that warrant mentioning.

Selective emitter [7]

The advantages of a selective-emitter cell include a low contact resistance owing to heavy doping underneath the metal grid, improved front-surface passivation of the lightly doped region between the grids, and reduced recombination under the metal contact. Nevertheless, the very material that gives the p-n junction its functionality also forms a significant barrier to light in the blue part of the spectrum.

Selective emitters address this issue by varying the amount of phosphorus across the surface of the cell. The basic principle is to deposit more phosphorus directly under the metal grid to improve the contact between the metal and the silicon, allowing electrons to migrate more efficiently. Additionally, decreasing the amount of phosphorus between the grid fingers reduces recombination losses, which improves the cell's blue response.

There are a number of approaches to creating selective emitters, including doped silver paste, screen printing, selective diffusion, laser doping, etchback, doping paste etchback, buried contact and ion implant. However, the disadvantage of each of these processes is that any improvement in the blue spectrum response is attenuated by the absorption of the blue spectrum by other module components (glass and ethylene vinyl acetate – EVA). It is estimated that these materials reduce the benefit of selective emitters by 50%. Until improvements at the module level allow the full value of selective emitters to be extracted in the field, the benefit of the more costly and complex selective-emitter cell processes will be reduced.

Heterojunction with intrinsic thin layer (HIT or HJT) [8]

In an HIT/HJT solar cell structure, an intrinsic a-Si layer followed by a p-type a-Si layer is deposited on a randomly textured n-type c-Si wafer to form a p-n heterojunction. On the other side of the c-Si, intrinsic and n-type a-Si layers are deposited to obtain a back-surface field (BSF) structure. On both sides of the doped a-Si layers, transparent conducting oxide (TCO) layers are formed, and finally metal grid electrodes are formed using a screen-printing method. By inserting the intrinsic a-Si layer, the defects on the c-Si surface can be passivated.

The HIT/HJT structure provides high performance, with the National Renewable Energy Laboratory (NREL) reporting approximately 23% efficiency. In addition, HIT/HJT cells exhibit a better temperature coefficient than conventional p-n c-Si solar cells. This technology may become more interesting now that some of the original patents have expired.

Metal wrap-through (MWT) [9]

MWT is one of many types of back-contact technologies. In MWT cells, the front metal grids are wrapped through via holes to the rear side of the wafer, reducing shading and surface recombination losses. On MWT modules the strategy of full back interconnection of the cells results in lower cell-to-module losses by avoiding much of the resistive loss in existing double-side interconnected H-pattern solar cells. The reported efficiency improvement using MWT is 0.3%.

Interdigitated back contact (IBC) [10]

IBC cells consist of a c-Si wafer and alternating lines (interdigitated stripes) of p-type and n-type doping. This cell architecture has the advantage that all of the electrical contacts to the p and n regions can be made on one side of the wafer. When the wafers are connected together into a module, the wiring is all done from one side. Efficiencies greater than 23% have been reported.

Another approach is to combine IBC with HIT/HJT (IBC-HJ). These cells have a very high efficiency potential of more than 24% and 25% on p-type and n-type wafers respectively. The IBC-HJ cell structure consists of a front side that is contactless and well passivated, and a back side that is formed of amorphous/crystalline silicon heterojunction contact structures.

One to watch

One of the ways to improve overall cell performance is to retain more of the photons that hit the cell surface – easier said than done. A variety of techniques are used, often in combination, from forming random pyramids to AR coatings. A relatively new entrant is a process that involves the etching of nanopores into the silicon surface. This process results in a surface that captures a portion of the light that would normally be reflected off the usual AR

Credit: Natcore Technology

Figure 2. Pyramidal texture etch (left) and the same type of wafer with a black silicon etch (right).

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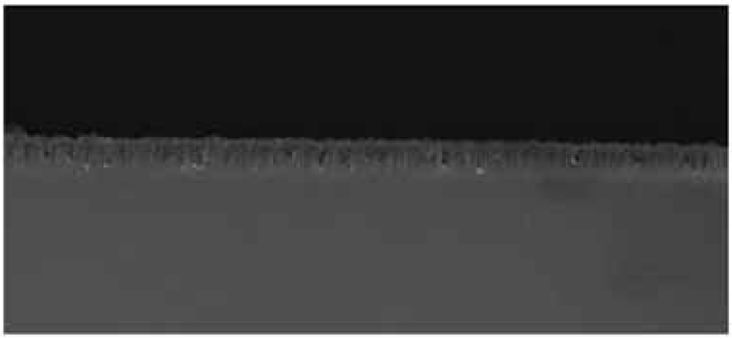
> "One of the ways to improve overall cell performance is to retain more of the photons that hit the cell surface."

Fig. 2 contrasts a commercial wafer having the standard pyramidal texture etch (left) and the same type of wafer with a black silicon etch (right). The wafer on the left still requires a silicon nitride AR layer to be added in order to reduce the reflectance from about 10% to about 5%. The wafer on the right does not need an additional AR layer to be added and has an average reflectance of about 1% or less.

Fig. 3 shows a high-magnification image of the cross section of a typical black silicon surface layer; a wet process step is used to create this layer. Fig. 4 shows a similar cross section of a black silicon layer, but one in which the pores have been filled and coated with silicon dioxide. The silicon dioxide is applied by a liquid-phase deposition (LPD) process at moderate temperatures (< 60°C).

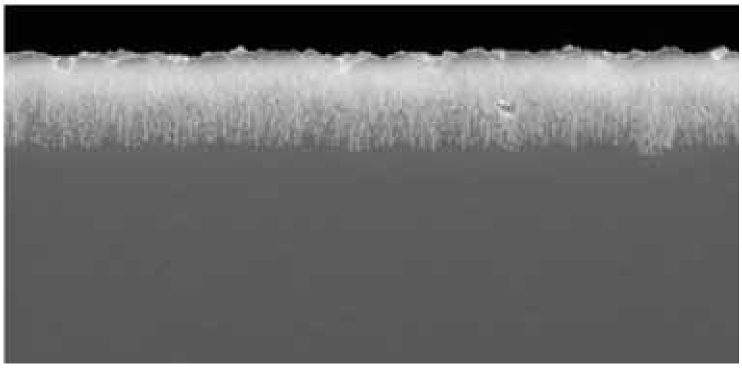
The silicon dioxide serves to passivate and protect the black silicon nanoporous structure. No further surface treatment is needed once the silicon dioxide has been deposited, and the wafer is ready for the usual screen-printed contact formation step of the cell line. The black silicon process is performed on a single wet station and eliminates the silicon nitride deposition step.

The step obviously incurs a cost, so the question is: how can this process be integrated in a manner that makes it cost effective? Fortunately, this is in part a replacement step; so, in order to be cost effective, it needs to be cost and value competitive relative to existing techniques. The combination of the nanopore creation and the deposition of a liquid phase oxide appears to be capable of being integrated into a single tool. The cost of the processes it may replace is thought to be approximately 10–12 cents per cell. Preliminary COO studies, including one discussed later in this paper, have been performed for a black silicon process: the new process is competitive at 12 cents, which translates (with rounding errors) to about $1 per conventional panel. If you can sell that panel for $1 more, then you have broken even. Even today, that is a relatively modest premium to pay given the added light captured by the process.



Credit: Natcore Technology

Figure 3. High-magnification image of the cross section of a typical black silicon surface layer.



Credit: Natcore Technology

Figure 4. LPD-process coated black silicon surface.

Case study

Our 'one to watch' process is nanopore formation using Natcore Technology's black silicon process as an example. In order for nanopore formation to be something worth adopting in the near future, not only does it need to pass the technical requirements, but it must also offer a business objective of high payback. This objective will be explored through a preliminary COO analysis.

COO review [11]

A more detailed discussion of COO can be found in the first paper in this series [2]. To review, the basic COO algorithm is described by:

$$C_U = \frac{C_F + C_V + C_Y}{L \times TPT \times Y_C \times U} \qquad (1)$$

where

C_U = cost per good unit (wafer, cell, module, etc.)
C_F = fixed cost
C_V = variable cost
C_Y = cost due to yield loss
L = process life
TPT = throughput
Y_C = composite yield
U = utilization

Overall equipment efficiency (OEE) review [12]

One of the most popular productivity metrics is OEE. It is based on reliability (mean time between failures – MTBF), maintainability (mean time to repair – MTTR), throughput, utilization and yield. All these factors are grouped into the following four sub-metrics of OEE:

1. Availability (joint measure of reliability and maintainability)
2. Operational efficiency
3. Throughput rate efficiency
4. Yield/quality rate

As seen in the above list, many parameters are required in order to

$$\text{OEE} = \frac{\text{Number of good units output in a specified period of time}}{\text{Theoretical throughput rate} \times \text{Time period}}$$

Equation 2.

Parameter	Value
Throughput	1300 wafers/hr
Wafer size	156mm
Process lifetime	7 years
MTBF	200 hours
MTTR	10 hours
Equipment cost	$2 million
Equipment yield	99.90%
Utilities (lifetime)	~$1.3 million
Consumables (lifetime)	~$2.4 million
Maintenance (lifetime)	~$1.6 million

Table 1. Major COO inputs.

calculate OEE. If the accuracy requirement is not a critical factor, the formula given in Equation 2 can be used to calculate an approximate OEE value.

Relationship between metrics

There are many equipment performance metrics at different levels. Although they may appear disjointed, this is not the case – they all fit nicely into a hierarchical tree. Fig. 5 depicts the hierarchical tree of the equipment performance metrics. As shown in the figure, when a time dimension is added to quality and safety, it becomes 'reliability'. Reliability and maintainability jointly make up 'availability'. When production speed efficiency, operational efficiency and production defect rate are combined with availability, it becomes 'productivity' (OEE). Acquisition and operational costs, along with productivity, make up 'life cycle cost' (LCC). When scrap, waste, consumable taxes, insurance and interest costs are added to LCC, and the total is normalized by the production volume, it becomes 'cost of ownership' (COO).

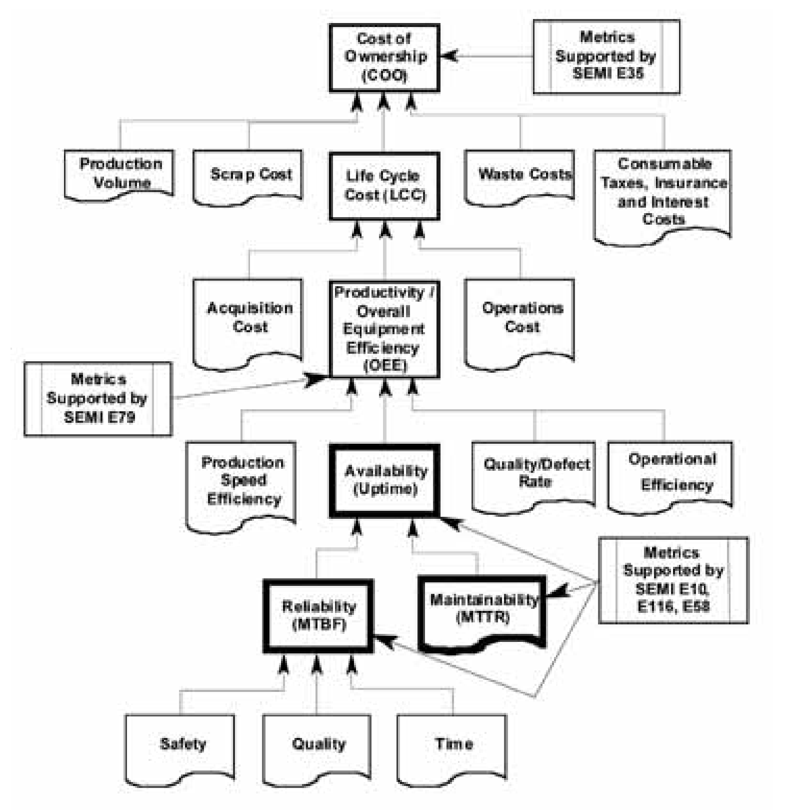


Figure 5. Hierarchy of equipment performance metrics [13].

Cost per system	$2,000,000
Number of systems required	1
Total depreciable costs	$2,225,000
Equipment utilization capability	90.99%
Production utilization capability	90.99%
Composite yield	99.90%
Good wafer equivalents out per week	198,526.93
Good wafer equivalent cost	
With scrap	$0.12
Without scrap	$0.12
Average monthly cost	
With scrap	$104,919
Without scrap	$103,883
Process scrap allocation	
Equipment yield	100.00%
Defect limited yield	0.00%
Parametric limited yield	0.00%
Equipment costs (over life of equipment)	$2,385,041
Per good wafer equivalent	$0.03
Per good cm^2 out	$0.0002
Recurring costs (over life of equipment)	$6,428,164
Per good wafer equivalent	$0.09
Per good cm^2 out	$0.0005
Total costs (over life of equipment)	$8,813,205
Per good wafer equivalent (cost of ownership)	$0.12
Per good wafer equivalent supported	$0.12
Per good cm^2 out	$0.0007
Per productive minute	$2.63

Table 2. COO results.

Cost of ownership inputs

This section presents the results of the COO analysis run on the black silicon process. Table 1 highlights the major input parameters.

In addition to the Table 1 parameters, the authors used, where required, example values from SEMI E35 [11] for administrative rates and overhead. These values were provided by SEMI North American members and may not be applicable to other geographic regions. However, it is the authors' experience that these example values do not impact the COO results on a relative basis.

Cost drivers

Examination of the detailed TWO COOL COO model [14] in Table 2 highlights the main cost and productivity factors. Recurring costs are approximately three times the initial capital costs over the life

Cost drivers per good wafer equivalent	
Material/consumables	$0.050
Depreciation	$0.031
Maintenance	$0.022
Labour	$0.014
Floor space costs	$0.002
Support personnel	$0.001
Scrap	$0.001
Training	$0.000
System qualification costs	$0.000
Other materials	$0.000
ESH preparation and permits	$0.000
Moves and rearrangements	$0.000
Other support services	$0.000

Table 3. Pareto of cost drivers.

Supply/ Consumable	Annual cost per system
Material 1	$103,567
Material 2	$79,208
Material 3	$54,947
Material 4	$37,148

Table 4. Annual supply/consumable costs.

of the process and are driven primarily by the cost of consumables. Next, the top cost drivers and opportunities for improvement will be looked at more closely.

> "The top Pareto costs are materials/consumables, depreciation and maintenance."

Table 3 takes a closer look at the cost breakdown according to the 13 categories specified in SEMI E35. The top Pareto costs are: materials/consumables, which include utilities, supplies, consumables and waste disposal; depreciation, which is impacted by equipment costs, throughput rate and utilization; and maintenance, including repair parts and technician labour.

The top two cost drivers account for two-thirds of the total COO. For this reason, attention will be focused on those areas when the cost sensitivities to input parameters that drive material/consumable and depreciation costs are examined.

Cost driver sensitivities

The first factors to be examined are supplies and consumables. Table 4 shows the annual costs per system by supply item. One of the issues in defining a sensitivity analysis for these items is their potential interrelationship with other factors. Changing the price/quality of the consumables could impact throughput,

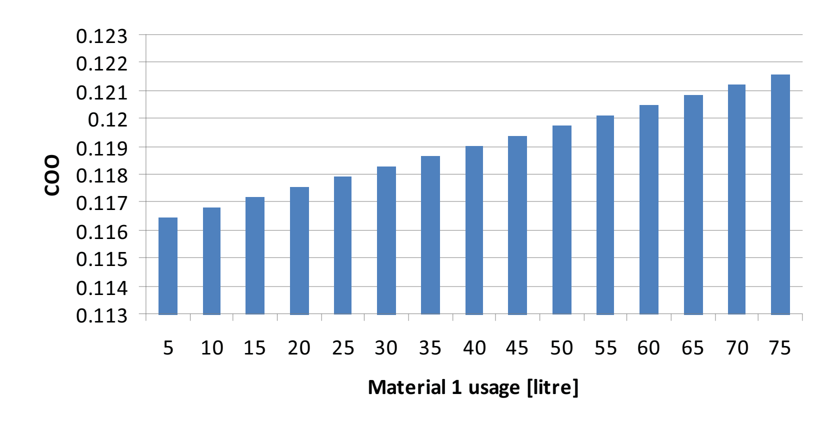


Figure 6. Sensitivity analysis of Material 1 quantity vs. COO.

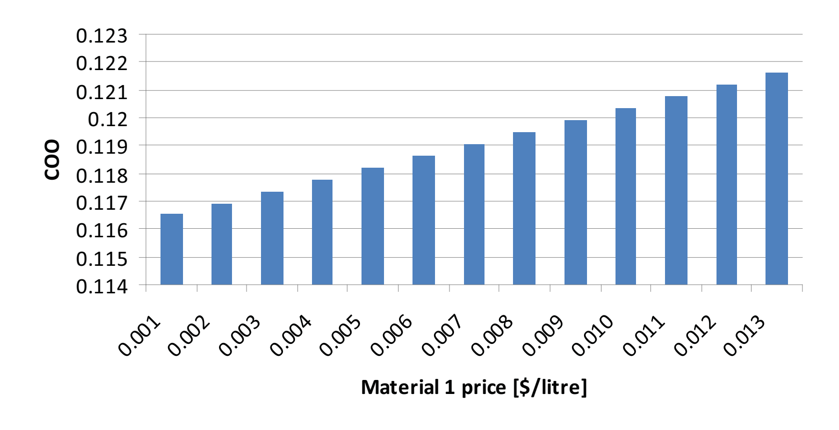


Figure 7. Sensitivity analysis of Material 1 price vs. COO.

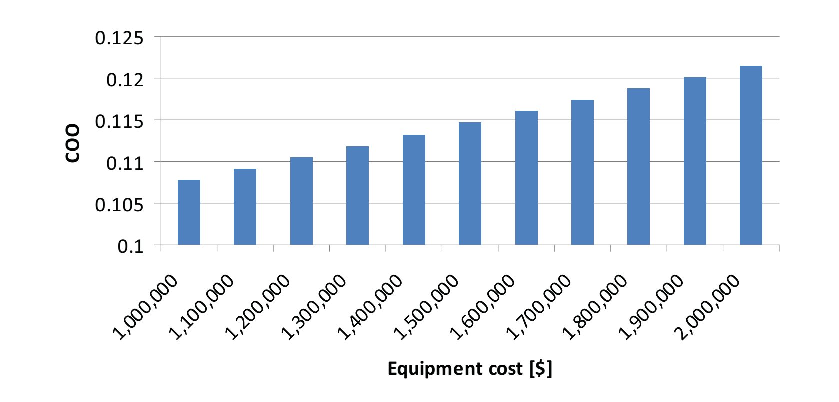


Figure 8. Sensitivity analysis of purchase price vs. COO.

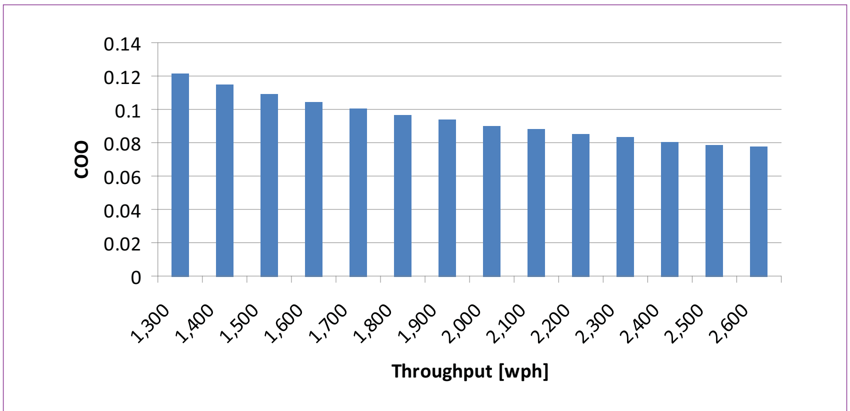


Figure 9. Sensitivity analysis of throughput vs. COO.

Overall equipment efficiency	90.90%
Availability efficiency	90.99%
Engineering usage	0.00 hr/week
Standby	0.00 hr/week
Hours available/system (productive time)	152.87 hr/week
Downtime	15.13 hr/week
Scheduled maintenance	7.00 hr/week
Unscheduled maintenance	7.92 hr/week
Test	0.00 hr/week
Assist	0.21 hr/week
Non-scheduled time	0.00 hr/week
Equipment uptime	152.87 hr/week
Total time	168.00 hr/week
Performance efficiency	100.00%
Throughput at capacity/system	1300.00 wafers/hr
Theoretical throughput	1300.00 wafers/hr
Operational efficiency	100.00%
Rate efficiency	100.00%
Quality efficiency	99.90%
Equipment yield	99.90%
Defect-limited yield	100.00%
Parametric-limited yield	100.00%
Alpha error factor	100.00%
Beta error factor	100.00%
Redo rate	0.00%

Table 5. OEE results.

consumption or yield; consumption changes could impact throughput and the conversion efficiency of the device. The cost benefits that could be achieved by reducing the consumption or cost per litre of Material 1 will be examined.

As can be seen from Fig. 6, the usage of Material 1 has a low impact on the total COO. This sensitivity analysis is based on one tank using Material 1; however, there are two tanks that use the majority of this material. Thus, a 50% reduction in usage provides approximately a 6% reduction in the total COO for the process. While it may not be possible to achieve this level of reduction and maintain process control, it certainly presents an opportunity for cost reduction.

Likewise, the price of Material 1 has a similar impact on the total COO (Fig. 7): a 50% reduction in price provides an approximate 6% reduction in the total COO for the process. It should be noted that the reason Material 1 has a low impact on COO is that there are several consumables used in the process and Material 1 represents only about one-third of those costs.

The factors impacting depreciation, purchase price and throughput will be discussed next. Purchase price has a moderate impact on COO in high-throughput tools, especially those with higher variable costs (Fig. 8). The cost impact in this case is approximately 1.2% per $100,000 (5%) change in purchase price.

On the other hand, as can be seen in Fig. 9, improvements in throughput can have a significant impact on COO, depending on whereabouts on the curve the equipment is operating. In this case, the equipment is operating at an average throughput of 1300 wafers/hour (wph), and an improvement of 100wph near the average has a greater than 5% impact on COO.

Overall equipment efficiency

Table 5 shows the OEE of the black silicon process step: as can be seen, on the basis of a maximum throughput rate of 1300wph, the OEE is in excess of 90%. One hundred per cent of the OEE losses in this model are attributed to availability efficiency primarily associated with equipment downtime (scheduled and unscheduled). Since this is a preliminary analysis of the process, the values of OEE and COO should be taken as potential opportunities only.

Conclusions

The PV industry is in a challenging phase. The overcapacity issues are exacerbated by changing government policies and increased competition external to the PV industry. Solar cell providers who do not evolve will get eaten alive. As counterintuitive as it might seem in a period when money is tight, companies need to spend money. They must invest in newer, higher-value technologies and lower-cost processes. It is not a choice.

An attempt has been made to pick the investment options that the authors see as having the largest paybacks in the near term. In each case, these options differentiate themselves from baseline processes by improving costs or adding value to the product – in some cases, both.

Continuous improvement has been the norm for solar research and development; it has been more challenging in fixed production lines. But as factories get larger and the scale increases, it becomes apparent that this continuous improvement will require a near-constant evolution within manufacturing operations.

> "Ultimately, tools like COO and factory-level cost modelling will be essential in determining product roadmaps."

The uncertainty this brings in difficult business conditions is not appealing. It does, however, argue for a well thought out, disciplined process regarding the choices to be made. The roadmaps that companies pursue need to be carefully evaluated for the best business decision – which may well differ from the most 'talked-about' technology. Ultimately, tools like COO and factory-level cost modelling will be essential in determining product roadmaps – integrating these methods into both short- and long-term decision processes may prove to be the difference between the companies that do not survive and those that thrive.

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Materials

Polysilicon prices set to rise in Q1 2013

According to market research firm IHS, polysilicon spot market prices are set to climb through to the end of March 2013. Spot market polysilicon volumes have declined significantly since a peak in May 2012 when the spot market accounted for 47% of total polysilicon sales due to producers selling from inventory due to overcapacity and weak demand. The spot market accounted for only 20% of total polysilicon sales in December 2012, indicating the lack of inventory overhang and a consequence of plummeting prices that forced the vast majority of small producers to shut plants when prices fell well below manufacturing costs. IHS said that polysilicon supply was finally adjusting to reduced sales, though cautioned that demand was expected to increase only modestly in 2013, keeping a lid on price rises as well as suppliers' ability to re-enter the market as prices would need to be in the US$25/kg range to be profitable.

Polysilicon spot market prices are set to climb.

Polysilicon News Focus

PV installation growth in 2013 to support polysilicon price rises

Market research firm, Bernreuter Research is forecasting PV installations could reach 36GW in 2013, driving renewed polysilicon demand. The latest forecast could provide significant relief for the struggling polysilicon sector, after high purity polysilicon spot market prices plummeted 59% in 2011, followed by a 47% decline in 2012, reaching a record low of US$15.35/kg, according to Bernreuter Research. Major growth markets for installations in 2013 are expected to be China, Japan and the US, which are expected to replace Europe as the key regions for PV installation growth.

Wacker ramping polysilicon production and ending short-time work due to demand

In a rapid turnaround from last year, Wacker Chemie has stopped short-time working schedules at its Burghausen polysilicon plants and will ramp capacity utilisation rates due to renewed demand. Wacker said it has sold more polysilicon in January than previously expected and recent new order intake was in excess of either inventory or current utilisation levels to meet demand. The company had reduced production utilisation rates to 80% of nameplate capacity in the third quarter of 2012 due to weak demand. Wacker noted that utilisation rates in the fourth quarter were lowered further to "to two-thirds of full utilisation."

Dow Corning 2012 income down 45% on polysilicon price declines

Significant price declines for polysilicon due to industry sector overcapacity impacted both revenue and net income at Dow Corning in 2012. The company reported full-year 2012 sales of US$6.12 billion, down 5% from 2011. Net income was U$188 million, down approximately 45%, compared to the prior year. Oversupply, economic volatility and high raw material costs were said to have been behind the reduced profit levels.

NPD Solarbuzz: Polysilicon plant utilisation rates fall below 70%

The continued crash in polysilicon prices in 2012 has finally brought some rational thinking to the sector as tier 1 suppliers have cut plant utilisation rates to below

Source: Dow Corning

Dow Corning's net income was U$188 million, down approximately 45%, from 2011.

70%, according to the latest figures from market research firm, NPD Solarbuzz.

Polysilicon prices have fallen drastically over the last two-years, ending at around US$15/kg on the spot market, a record low. Structural overcapacity and weaker than expected demand were the driving influences, forcing many companies to shutdown plants completely or exit the sector altogether. However, in 2012 major high-volume producers had continued to keep utilization rates (typically in the 90% range) high to keep production costs as low as possible. According to NPD Solarbuzz, analysis shows that despite a 70% ASP decline between the first quarter of 2011 and the second quarter of 2012, producers maintained these high utilization rates.

GCL-Poly's polysilicon and wafer shipments plummet in Q3

Shipments of both polysilicon and solar wafers at GCL-Poly, China's largest producer, fell significantly in the third quarter of 2011 underlining the overall weakness in demand from major tier 1 module manufacturing customers based in China. Polysilicon production also fell significantly in the quarter to 7,631MT, down from 12,998MT in 2Q 2012. Shipments of polysilicon followed the production decline as GCL-Poly reported only 657MT of shipments in Q3, down from 5,971MT in Q2. Wafer production slowed to 1,689MW in Q3, down from 1,878MW in Q2.

GCL-Poly said that it had been impacted by several factors which included the European debt crisis, US anti-dumping and countervailing duties and the ASP decline in polysilicon and wafers.

LDK secures loan for silicon plant upgrades

PV manufacturer LDK Solar has secured a US$70,700,000 loan from the China Development Bank to finance technology upgrades at its Mahong polysilicon plant. The company plans to use the money primarily to invest in hydrochlorination technology, said to be crucial in reducing the costs of silicon production at the plant.

LDK said it had already invested US$1.9 billion in the plant, a factor explaining the company's high debt ratio.

REC to expand module production in 2013; massive polysilicon asset write down

Renewable Energy Corporation's fourth quarter financial results were masked by massive US$325.7 million impairment on fixed assets related to its polysilicon operations (REC Silicon) in the US. REC Silicon recognized impairments of fixed assets of US$340.3 million for the full-year. The company reported fourth quarter 2012 revenues of US$305.2 million, approximately 12% higher than the previous quarter.

Source: Dow REC

REC's fourth quarter financial results were masked by massive US$325.7 million impairment on fixed assets.

Polysilicon sales at Wacker continue to decline on pricing pressure

Preliminary fourth quarter polysilicon revenue at Wacker continued to decline throughout 2012, due to continued pricing pressure. Wacker's polysilicon business reported preliminary fourth quarter 2012 sales of €213 million (US$280 million), down from €269.1 million in the third quarter and down significantly from €366.6 million (42% fall) in the first quarter. Sales have therefore declined each quarter of 2012. The company also reported an EBITDA decline of 47% to €78 million, compared to an EBITDA of €150.1 million in the first quarter of 2012.

Yingli Green boosts wafer quality while lowering costs

A partnership project to increase multicrystalline ingot casting quality and lower production costs at Yingli Green has been hailed a success. As part of the project, Yingli Green's ingot furnaces have been fully-upgraded with a new gas refrigeration process. Yingli Green said that experimental results from wafers produced from the upgraded ingot furnaces delivered solar cells with a best average conversion efficiency of 17.75%. The conversion efficiency increase is inline with Yingli Green's Q3 2012 guidance that commercial-scale multicrystalline cell efficiencies would reach 17.5% by the end of 2012.

Module Materials News Focus

STR Holdings to lose First Solar as major customer

PV module encapsulant material supplier, STR Holdings hit by the pending loss of its largest customer, First Solar, said that its restructuring efforts would result in a workforce reduction of approximately 160, or 32% of its global workforce.

Headcount reductions relate to the planned closure of its manufacturing plant in East Windsor, Connecticut, as well as job losses at its manufacturing facilities in Spain and Malaysia. Job losses were also planned at its headquarters in Enfield, Connecticut.

In 2012, STR had a US-based backsheet nameplate capacity of 2.9GW and the same nameplate capacity at its plant in Spain. The East Windsor plant also housed a 20,000 square foot R&D facility. Backsheet nameplate capacity in Malaysia

Source: First Solar

STR Holdings has lost its largest customer, First Solar.

Source: DuPont

Silver inks and pastes used in the PV sector have been predicted to decline from a value of US$4.9 billion in 2013.

stood at 3.6GW in 2012 but had a potential capacity of 5GW.

Dow Corning and Crystal Solar to partner on high-efficiency silicon venture

Silicon manufacturer Dow Corning and start-up Crystal Solar have announced a business relationship to develop high-performance silicon-based materials for PV cells and modules. The two companies also plan to jointly develop new products for building-integrated PV applications. Dow Corning said it would help Crystal Solar further develop its ultra-thin silicon technology, providing the company with access to its materials and silicon supply chain expertise. Crystal solar claims its 'direct gas to wafer' process enables it to develop ultra-thin silicon wafers that offer greater efficiency at lower costs to its rivals.

Dow Chemical to further develop and expand capacity of ENLIGHT module encapsulant

Having recently introduced its latest ENLIGHT polyolefin PV module encapsulant films, Dow Chemical has said it will be further developing the films and adding manufacturing capacity at its integrated site in Schkopau, Germany, in 2013. The company had previously commenced production of the films at its plant in Ohio, US, in 2010, while adding further capacity this year in Thailand.

ReneSola modules obtain UL certification for 600V and 1000V systems in US

ReneSola has announced its 72-cell polysilicon modules have been listed by UL as meeting required standards for use in PV systems up to 1,000 volts. At the same time, the company's 60-cell and 72-cell modules have been listed by UL as meeting required standards for use in PV systems up to 600 volts.

ReneSola's 72-cell module line is currently undergoing testing for certification from the California Energy Commission and the California Solar Initiative.

Madico's Protekt technology granted JET certification

Madico, a backsheet manufacturer, has received certification from Japan's Electrical Safety & Environment Technology Laboratories (JET) for its Protekt backsheets.

Madico's Protekt backsheets for solar modules met specific qualifications in order to qualify for JET certification including the completion of safety conformity tests and demonstrating a manufacturing environment that has high quality control processes. Additionally, JET confirmed that module constructions met the long-term performance requirements of the region.

Business News Focus

Solar industry demand for silver pastes and inks remains in decline

Market research firm, NanoMarkets said in a new report that sales of silver inks and pastes used in the PV sector would decline from a value of US$4.9 billion in 2013 to around US$3.4 billion in 2020.

Demand from the PV sector was continuing to be a drag on the whole silver pastes and inks, according to the company's report, *The Silver Inks and Pastes Market 2013-2020*. Cost sensitivity due to aggressive PV module ASP declines led major PV manufacturers to attempt to reduce silver paste consumption. Severe overcapacity and consolidation and capitulation have also impacted consumption rates.

Traditional thick-film applications for printed silver are expected to use US$2.4 billion worth of silver inks and pastes in 2013, but continue a steady growth path to US$3.4 billion by 2020.

Ferro finds buyer for conductive paste business

Less than six-months after Ferro put its conductive paste business up for sale, major materials supplier, Heraeus has purchased the business for an undisclosed sum.

In a brief statement, Heraeus said that the acquisition includes all associated intellectual property regarding metallization pastes for solar cells. Ferro has spent years developing and launching a string of new conductive pastes that covered the spectrum of requirements within the PV industry but failed to gain market traction against the market leaders such as DuPont and Heraeus.

Lanco Infratech on the search for investors to expand PV capacity

Lanco Infratech, an Indian power generation company involved in EPC and solar among others requires funds to add 500MW of PV capacity every year in the next three years as coal availability becomes more limited and the price of fuel imports rises. Lanco is building a plant that will have the capacity to produce 1,800 tons of polysilicon, 100MW of ingots and wafers, and 75MW of modules a year. However, the company is expecting to increase the module production capacity to 250MW in three years.

Product Reviews

Huntsman Advanced Materials

Huntsman Advanced Materials develops new encapsulating system for PV Inverters

Product Outline: Huntsman Advanced Materials has launched a new product for potting solar inverters. The polyurethane system 'Arathane' CW 5660/HY 5610 has been designed to meet the key requirements of inverters for PV applications.

Problem: Fast and efficient processing at ambient temperatures requires an encapsulant with excellent flowability together with a reasonable low mix viscosity. On the other hand, the encapsulant should provide a reasonable high thermal conductivity to remove produced heat in a fast and efficient way. Long-term thermal endurance at higher temperatures combined with low-temperature flexibility is one of the main challenges for its development.

Solution: High thermal conductivity is one key element for encapsulants in the design of inverters allowing fast dissipation of produced heat. For that reason the system has been formulated using a mineral filler with an acceptable high filler load, keeping required low viscosity in mind. The system offers a thermal conductivity of 0.7W/mK together with a mix viscosity of only 1900mPa/s at room temperature. High thermal endurance combined with a low modulus of elasticity has been balanced through an appropriate polymer backbone. The first storage trials at high temperatures indicate a possible thermal class F material in accordance with IEC 60085.

Applications: The system enables fast and efficient casting of large PV inverters.

Platform: Arathane CW 5660/HY 5610 is a flexible multipurpose polyurethane system for pressure-sensitive devices, encapsulation of printed circuit boards and inductivities.

Availability: January 2013 onwards.

PPG Industries

PPG's heat-strengthened 2mm glass reduces module costs and improves efficiency

Product Outline: PPG Industries' flat glass business unit says it can now manufacture heat-strengthened glass of less than 3mm in thickness, which makes it among the first major glass manufacturers in North America to offer this capability. PPG offers the Solarphire glass in heat-strengthened configuration with thicknesses of 2mm, 2.5mm and 2.7mm.

Problem: The added strength gives thin glass used in various solar applications that require resistance to wind load, hail impact and other environmental hazards the ability to meet UL and IEC standards.

Solution: When incorporated into solar modules, heat-strengthened thin glass permits more sunlight to reach the active layer, which enhances the conversion of sunlight into energy and increases power output. With 2mm Solarphire glass, solar transmittance is claimed to be improved by 0.3% compared to 3.2mm glass and by 0.5% compared to 4mm glass. Heat-strengthened thin glass is also claimed to give PV manufacturers the opportunity to cut downstream costs by eliminating traditional protective plastic or polyvinyl fluoride backing sheet material.

Applications: PV, CPV and CSP modules.

Platform: PPG can produce heat-strengthened glass with surface-compression strength that exceeds that of fully tempered glass while achieving ASTM C1048 standards for flatness.

Availability: November 2012 onwards.

Potential for mono-cast material to achieve high efficiencies in mass production

Milica Mrcarica, Photovoltech NV, Tienen, Belgium

ABSTRACT

Despite the drop in price of silicon wafers, they are still one of the main factors influencing the cost and performance of Si-based solar cells. These two consequences have initiated a growing commercial interest in mono-cast (cast-mono, mono-like or quasi-mono) Si wafers, supported by R&D in the areas of material characterization, correlation with cell efficiencies, and mono-cast material use in advanced cell technologies. This paper gives a broad overview and comparison of commercially available grades of mono-cast material from different suppliers. The performance of the material from production in high-throughput screen-printing lines, as well as an analysis of the main material characteristics influencing these results, is presented. A characterization using a lifetime tester and a photoluminescence (PL) imaging tool has shown that not only grain boundaries but also dislocations could cause a drop in cell V_{oc} of more than 15mV. Wafers with large surface areas of <100> Si lattice planes, when processed with anisotropic texturing, could yield an increase in I_{sc} greater than 400mA for 6" substrates, as compared to the isotropic-textured equivalents. Furthermore, when a high-grade mono-cast material processed in anisotropic texturing was compared with CZ mono material from the same supplier and of the same resistivity, light-induced degradation (LID), presented as combined V_{oc} and I_{sc} degradation, was only one-third of that in CZ material. However, although mono-cast material has the potential to increase cell line performance to the same level as that gained by important process and technological improvements, it imposes very high requirements for better material sorting in order to achieve stable cell electrical performance and module aesthetics acceptable to the market.

Introduction

According to the SEMI ITRPV [1], Si wafers represent more than 50% of the final cell cost. It is envisaged that a reduction of this cost will happen not only by reducing wafer thickness, but also by improving material quality – mainly multicrystalline Si (mc-Si) – so that J_{0bulk} is reduced from 600 to 200fA/cm^2 by the year 2020. The producers of mc-Si wafers are taking two paths to reach this target. One is the improvement of the casting conditions for high-performance mc-Si (HPM) wafers [2]. A more promising path, however, is the casting of Si material with large grains of <100> orientation (mono-casting), first announced by BP Solar in 2006 [3]; more recently, dendritic growth research was reported by IMT and Kyoto University Japan in 2009 [4,5].

Mono-casting technology has been commercialized through the development of silicon monocrystalline growth casting furnaces [6]. High-throughput production using the mono-casting approach is now under way at GCL, LDK, ReneSola, Pillar, JA Solar and other silicon ingot and cell manufacturing companies [7,8]. Although the suppliers of mono-cast material claim an increase in cell efficiency of up to 1% absolute, and a reduction in light-induced degradation (LID) and cell-to-module (CTM) losses, mono-cast does not have a significant share in mass cell production. The ITRPV sees the share of mono-cast increasing to 50% by the year 2020.

The growing commercial interest in mono-cast material has been supported by R&D in the area of its impact on cell performance and material characterization [9–11], as well as its use in advanced technologies [12,13]. A promising result of 20.2% efficiency for n-type premium-grade mono-cast material with a heterojunction cell concept has been published [14].

> "The ITRPV sees the share of mono-cast increasing to 50% by the year 2020."

Comparison of supplier materials in production

Table 1 presents the different suppliers' classes of mono-cast wafers covered in this

Wafer	Tested	Mono <100> Area (M)			Ingot split			Wafering process	Texturing	
supplier	classes	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3		Isotropic	Anisotropic
A	C1,C2,C3	M ≥ 90%	70% ≤ M < 90%	M ≤ 70%	25%	15%	60%	Wire saw	C1	C1,C2,C3
B*	C1,C2,C3	M ≥ 90%	70% ≤ M < 90%	M ≤ 70%	57%	29%	14%	Wire saw		C1,C2,C3
C	C1,C2,C4	M ≥ 90%	40% ≤ M < 90%	M ≤ 40%	30%	40%	30%	Wire saw		C1,C2,C3
D	C2,C3	M ≥ 85%	70% ≤ M < 85%	20% ≤ M < 70%	Unknown			Wire saw		C2,C3
E**	C1	M = 100%	N/A	N/A	100%			Diamond wire saw	C1	

* Supplier B, a standard supplier of mc-Si wafers, was used as a benchmark in this study

** Material not commercially available

Table 1. A review of the suppliers' classes, the ingot split as indicated by the suppliers, and the wafering and texturing processes.

work. Before shipment of the material, the classes are sorted visually by the suppliers on the basis of the ratio or percentage of <100> area on the wafer. This sorting of the material into classes by the suppliers is qualitative and results in high variations within the batch, from batch to batch, and from supplier to supplier.

Electrical performance

Evaluating the different mono-cast wafer classes and suppliers and benchmarking against mc-Si material in production was a challenging task. It is well known from production practice that mc-Si wafer variations and/or process noise could result in significant differences in cell line performance on different occasions, even for the same wafer supplier. Production runs were performed on the same production screen-printing line, and with a process set-up for mc-Si material using batch isotropic texturing. At that stage, no attempt was made to optimize the process for different materials; an exception was

Wafer	Variable	Abs Δ efficiency [%]				Abs Δ V_{oc} [mV]				Abs Δ I_{sc} [A]				Abs Δ *FF* [%]			
supplier	Class	Mean	Min	Max	STD	Mean	Min	Max	STD	Mean	Min	Max	STD	Mean	Min	Max	STD
A	1	0.58	–1.73	1.21	0.37	7.46	–21.93	15.88	4.72	0.15	–0.63	0.33	0.10	0.41	–5.02	1.31	0.41
	2	0.26	–2.58	1.12	0.42	2.56	–26.08	14.98	5.95	0.08	–0.97	0.31	0.11	0.16	–3.40	1.27	0.47
	3	0.02	–4.65	1.11	0.34	–1.00	–28.64	14.46	5.05	0.03	–2.20	0.28	0.09	–0.10	–11.99	1.09	0.46
B	1	0.52	–0.41	0.93	0.23	8.49	–4.14	13.02	2.30	0.14	–0.13	0.25	0.06	0.12	–1.31	0.87	0.29
	2	0.28	–0.18	0.81	0.36	5.18	–1.08	12.59	5.09	0.07	–0.08	0.22	0.10	–0.01	–0.93	0.51	0.27
	3	–0.13	–0.77	0.56	0.30	–1.00	–6.75	8.32	4.03	–0.05	–0.20	0.14	0.09	0.00	–1.91	0.35	0.24
C	1	0.48	–0.72	1.02	0.49	7.58	–5.14	13.86	6.45	0.23	–0.04	0.37	0.14	–0.84	–3.04	–0.25	0.45
	2	0.28	–1.18	0.85	0.34	4.37	–4.85	11.29	4.14	0.18	–0.04	0.34	0.10	–0.87	–4.82	–0.31	0.53
	3	0.03	–0.60	0.69	0.23	–0.07	–4.55	8.39	2.69	0.09	–0.03	0.26	0.06	–0.72	–4.57	–0.09	0.48
D	2	0.24	–0.42	0.76	0.26	4.88	–3.97	11.46	3.48	0.05	–0.12	0.21	0.07	0.03	–1.44	0.60	0.25
	3	0.11	–0.70	0.43	0.19	0.27	–12.50	4.75	2.96	0.14	0.04	0.24	0.05	–0.77	–2.48	–0.12	0.50
E*	1	0.80	–0.42	1.27	0.28	–1.14	–8.67	5.86	3.27	0.38	–0.11	0.51	0.09	0.36	–1.17	0.96	0.37
B	mc-Si	0.00	–1.98	0.70	0.33	0.00	–23.72	12.91	5.40	0.00	–0.39	0.17	0.08	0.00	–7.95	0.78	0.51

* Group E, diamond wire saw, anisotropic texturing

Table 2. Absolute changes in efficiency, V_{oc}, I_{sc} and fill factor (*FF*) for the different classes of mono-cast wafers from various suppliers. The values are normalized to the mc-Si material from supplier B, used as the standard wafer supplier on the production line.

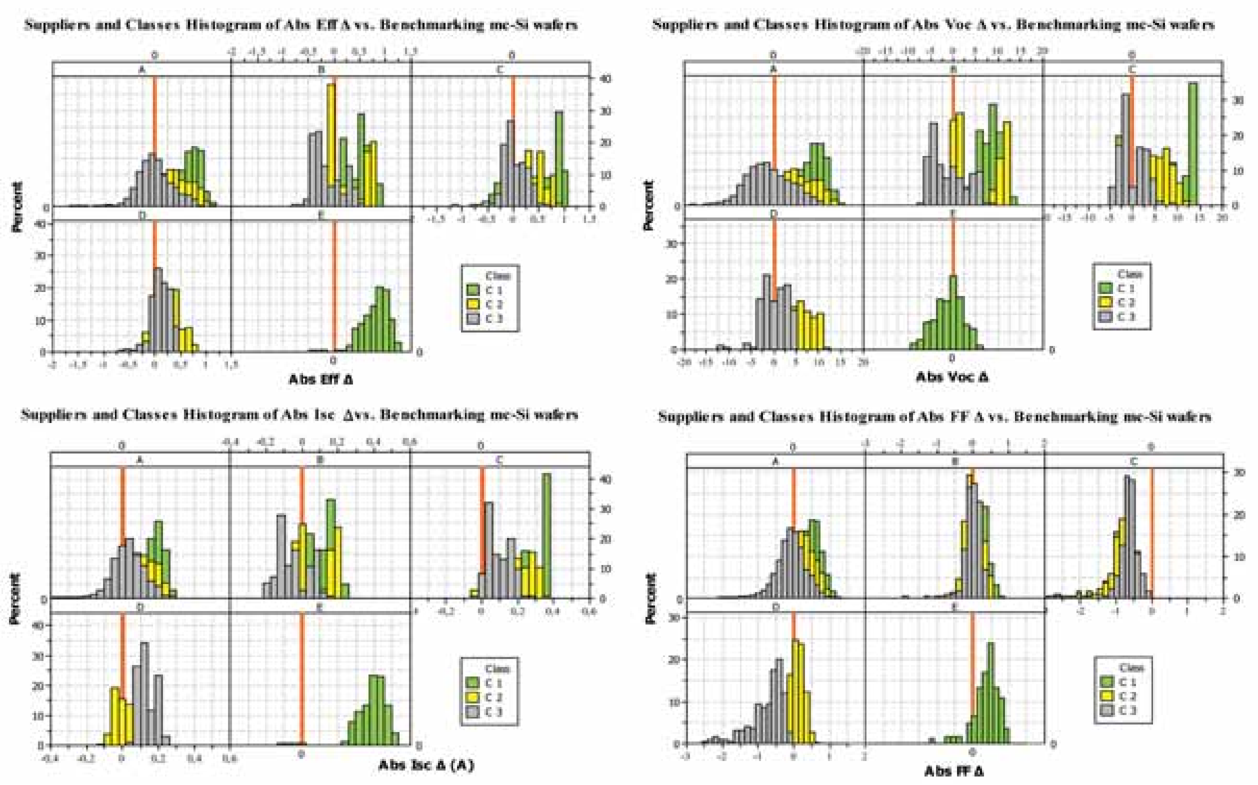

Figure 1. Distribution of the absolute efficiency, V_{oc}, I_{sc} and *FF* differences compared with the average values for the performance of mc-Si wafers from supplier B (denoted by reference line 0 in red).


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the material from supplier E, to which in-line anisotropic texturing was applied. The mc-Si material from supplier B (used for comparison purposes in this analysis and a standard material in production) was evaluated and averaged over different production times and batches.

The advantages of mono-cast material became apparent: a significant increase (especially for the premium class) in V_{oc} of up to 9mV and in I_{sc} of to 230mA for isotropic textured wafers. The enhanced I_{sc} of 380mA for supplier E results from the low reflectance achieved by the anisotropic texturing process. The change in *FF* was not systematic and depends more on the process variation or non-optimized process for different wafer materials. The electrical property results are summarized in Table 2.

The improvement in overall performance of mono-cast material is also due to the distribution shift towards higher performing cell bins, as shown in Fig. 1. Supplier A has the highest spread in V_{oc} and I_{sc}, but also the best potential for achieving the highest values in V_{oc} and I_{sc}. Suppliers A, B and C show drops in V_{oc} and I_{sc} for class 3, and supplier E even for class 1, compared with mc-Si wafers. This is not the case, however, for supplier D, which also exhibits the lowest variation in V_{oc} and I_{sc}. For all the classes from all the suppliers, mono-cast material demonstrates a high variation and spread inside each class, sometimes even higher than mc-Si material. This outcome is due not only to the lack of suitable sorting but also to the high variation in internal material structure.

Understanding material structure and its influence on cell performance

A Sinton instruments WCT-IL800 in-line tool was used for lifetime, resistivity and trap density measurements of the representative groups of as-cut wafers. Table 3 presents a summary of the wafer resistivity and lifetime measurements; the distribution of wafer trap density is shown in Fig. 2.

There was no direct correlation between the as-cut wafers' resistivity, lifetime and trap density and the cells' electrical performance: suppliers A and C have higher resistivities and lifetimes, but not higher gains in V_{oc} and I_{sc}. Variations in resistivity and lifetime, however, seem to be contributors to the variations in V_{oc} and I_{sc}: supplier E and D show lower STDs for wafer and cell performance. Further and more detailed study of well-sorted wafers could provide a better understanding of these dependencies.

"There was no direct correlation between the as-cut wafers' resistivity, lifetime and trap density and the cells' electrical performance."

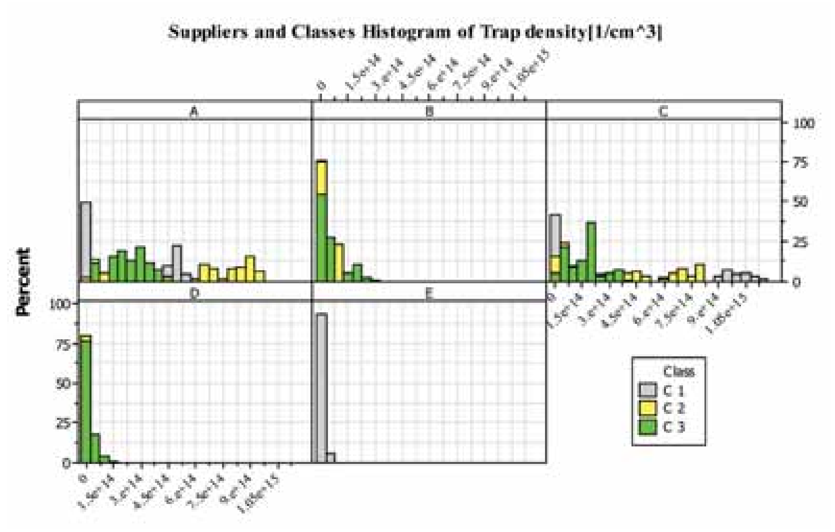


Figure 2. Trap density measurements from in-line testing for the different suppliers and classes of as-cut wafers.

The photoluminescence (PL) analysis was performed on a BT Imaging tool LIS-R1. For supplier C, PL imaging and J_0 imaging was done using a PLpix system from Solar Centrum Institute of Stuttgart. The PL imaging carried out on selected wafers and cells of suppliers and classes reveals the internal material structure and its impact on the finished cell, as shown in Fig. 3.

The same classes from different suppliers show similar structures. For supplier A, the wafer grain boundaries decrease in the premium classes, and the level of dislocations is low. Wafers with an entire area of <100> show the positions of the CZ seed plates from casting, but these dislocations do not have a significant impact on cell performance. The structure for supplier B is similar to that for supplier A (as shown in the PL images for as-cut wafers): depending on

Wafer	Variable	Resistivity [Ωcm]				Lifetime [μs]			
supplier	Class	Mean	Min	Max	STD	Mean	Min	Max	STD
A	1	2.01	1.70	2.60	0.33	0.98	0.84	1.11	0.06
	2	2.17	1.60	2.60	0.31	1.00	0.79	1.11	0.05
	3	1.99	1.80	2.40	0.13	0.95	0.71	1.03	0.05
B	1	1.34	1.21	1.47	0.07	0.86	0.44	0.94	0.06
	2	1.33	1.13	1.63	0.11	0.79	0.26	1.01	0.16
	3	1.26	1.08	1.42	0.08	0.80	0.65	0.90	0.05
C	1	2.11	1.71	2.55	0.22	0.93	0.62	1.17	0.11
	2	2.22	1.86	2.91	0.26	1.03	0.89	1.14	0.06
	3	1.94	1.58	2.50	0.17	0.92	0.61	1.07	0.09
D	2	1.54	1.30	1.80	0.12	0.91	0.74	1.03	0.05
	3	1.50	1.00	1.80	0.14	0.88	0.65	1.03	0.08
E	1	1.54	1.40	1.70	0.08	0.88	0.80	0.94	0.03

Table 3. Summary of resistivity and lifetime measurements from in-line testing for different suppliers and classes of as-cut wafers.

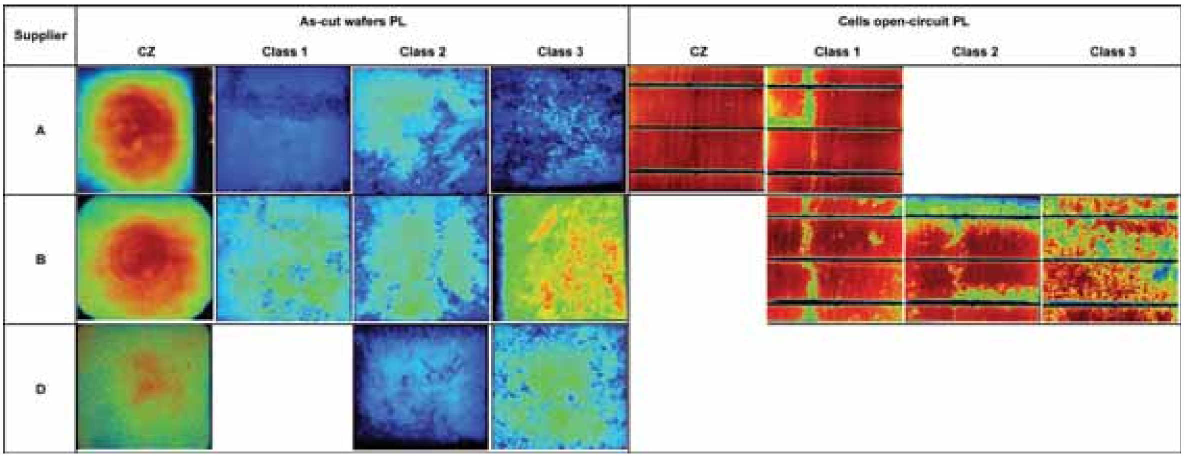
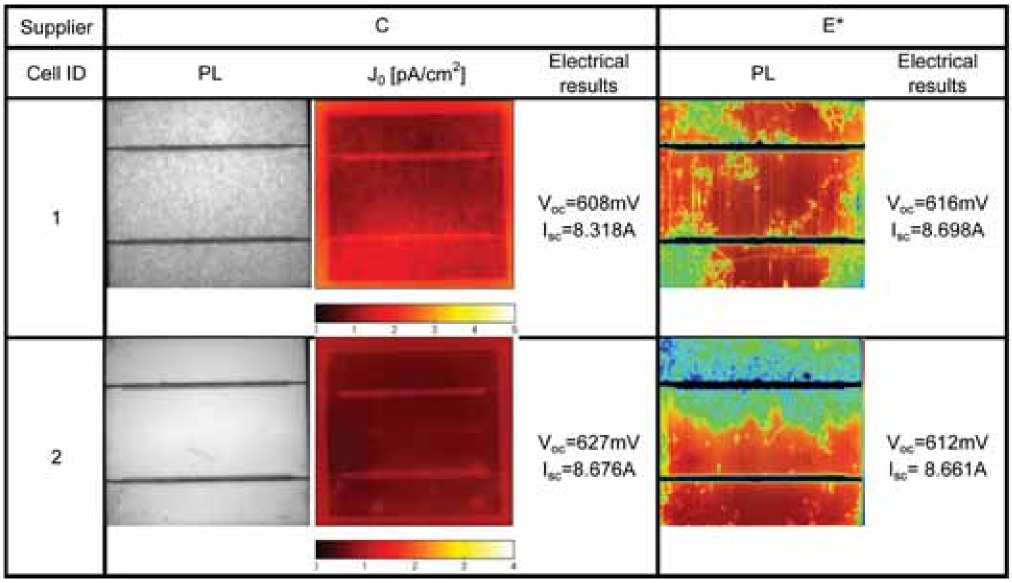


Figure 3. Uncalibrated PL images of the as-cut wafers of different classes from various suppliers (left) and PL images of representative cells (right). CZ and class 1 cells had anisotropic texturing. For supplier A, CZ cell efficiency = 18.54% and class 1 cell efficiency = 18.42%.



*Anisotropic texturing

Figure 4. PL images and corresponding V_{oc} and I_{sc} for finished cells from suppliers C and E created from the wafers with single crystal appearance.

the class, the grain boundaries decrease and the level of dislocations is variable. Supplier D is similar to supplier A but has fewer grain boundaries in class 3 than in the same class of supplier A. Supplier C has a large number of wafers in class 1 with the appearance of single <100> crystal. These wafers have the potential to yield high I_{sc} and V_{oc}, even with isotropic texturing.

Some of the wafers from certain batches, however, show a high level of dislocation, which is detrimental to V_{oc} and J_0, as shown in Fig. 4. Supplier E's wafers also have the single crystal appearance and no grain boundaries, but a high level of dislocation, decreasing V_{oc} to the same level as (or below) that for mc-Si wafers (Fig. 4). The efficiency of supplier E is above 17% because of anisotropic texturing, resulting in low cell reflectance.

Achieving high efficiencies with mono-cast wafers

Smaller-scale groups of supplier B classes 1–3 and supplier A class 1 were processed through isotropic texturing and under similar process conditions to those for cell line set-up using standard screen-printing technology. These groups were compared with supplier A class 1 mono-cast and supplier A CZ wafers processed through an in-line anisotropic texturing process. All wafers had between 1.5Ωcm and 2.0Ωcm resistivity. The results are shown in Fig. 5.

Supplier A's wafers have a narrower distribution and better performance than high-grade wafers from supplier B; however, the top group of wafers in B produced efficiencies close to 18% without anisotropic texturing and yielded a V_{oc} of 632mV. A comparison of different grades of material has confirmed once again the critical impact of material structure on cell performance, as well as the need for a good wafer-sorting system.

Performing anisotropic texturing on class 1 mono-cast wafers has an impact on I_{sc}, and thus on efficiency, which is greater than that gained by a change in class of mono-cast wafer. The increase in efficiency is greater than 0.8% absolute with anisotropic texturing compared to isotropic texturing. This improvement, driven by an increase in I_{sc} of 420mA at the cell level with reference to isotropic texturing, is remarkable and of greater impact than the difference between mono-cast material of class 1 and CZ material. Mono CZ wafers have a higher V_{oc} (by 2mV) than mono-cast, and similar I_{sc}.

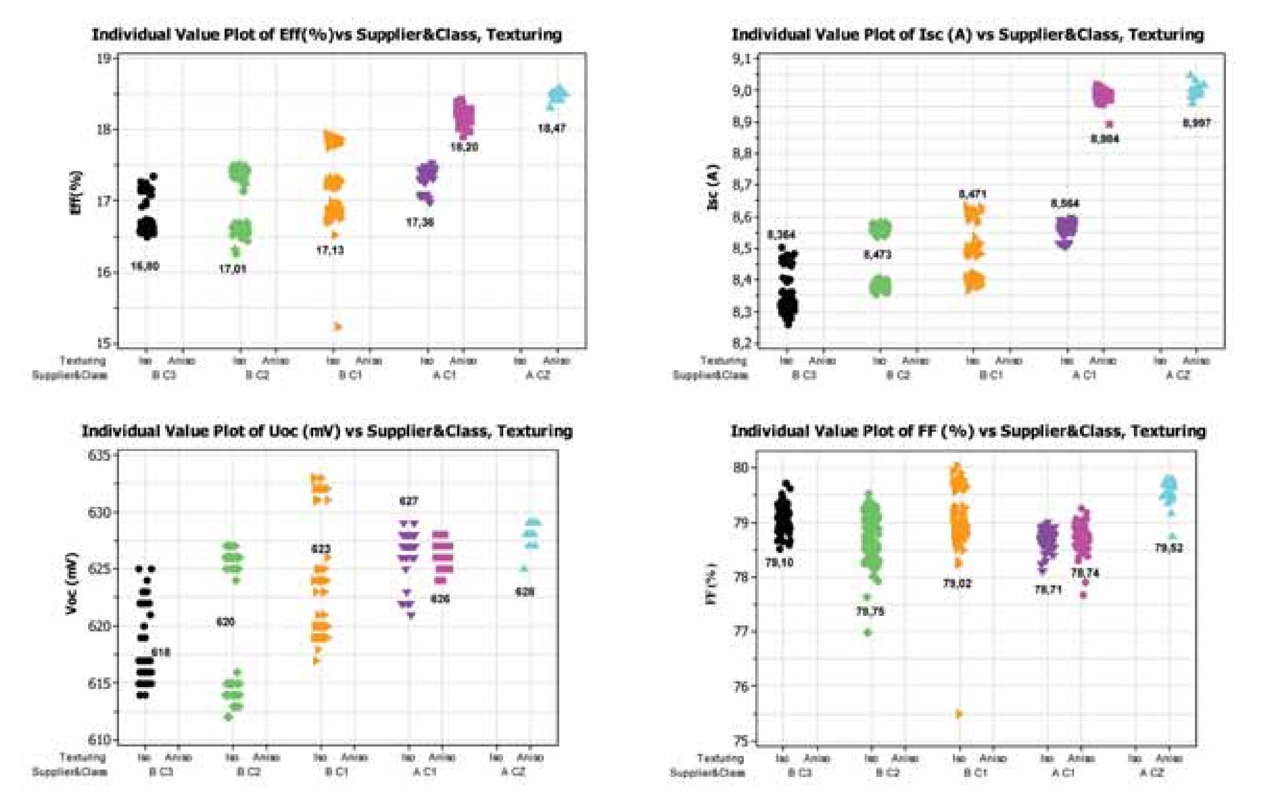


Figure 5. Comparison of the electrical performance of isotropic texturing groups of classes 1–3 of mono-cast wafers from supplier B and class 1 from supplier A, with anisotropic texturing groups of class 1 mono-cast and CZ material from supplier A.

"The anisotropic texturing process offers the highest potential for improving mono-cast efficiency."

The anisotropic texturing process offers the highest potential for improving mono-cast efficiency because it is possible to have almost the whole surface with <111> orientation and low reflectance. However, for the grains with different orientations, this could cause cosmetic issues at the cell and module levels, owing to the significant reflectance range at the wafer level and at the wafer to wafer level. It is for this reason that texturing of mono-cast material (and

Cell ID	Supplier	Class	Texture	I_{sc} Δ [%]	V_{oc} Δ [%]	Total Δ [%]
A CZ #1a	A	CZ	Anisotropic	– 0.94	– 0.78	– 1.71
A CZ #2a	A	CZ	Anisotropic	– 0.88	– 0.59	– 1.47
A C1#1a	A	C1	Anisotropic	– 0.34	– 0.08	– 0.42
A C1#2a	A	C1	Anisotropic	– 0.47	– 0.16	– 0.62
A C1#1	A	C1	Isotropic	– 0.29	– 0.10	– 0.38
A C1#2	A	C1	Isotropic	– 0.36	– 0.22	– 0.58
B C1#1	B	C1	Isotropic	– 0.47	– 0.08	– 0.55
B C1#2	B	C1	Isotropic	– 0.65	– 0.19	– 0.84
B C3#1	B	C3	Isotropic	– 0.30	– 0.06	– 0.37
B C3#2	B	C3	Isotropic	– 0.44	– 0.11	– 0.55
CZ average				– 0.91	– 0.68	– 1.59
Mono-cast average				– 0.42	– 0.13	– 0.54

Table 4. Response to LID of mono-cast wafers and CZ wafers with 1.5–2.0Ωcm resistivities.

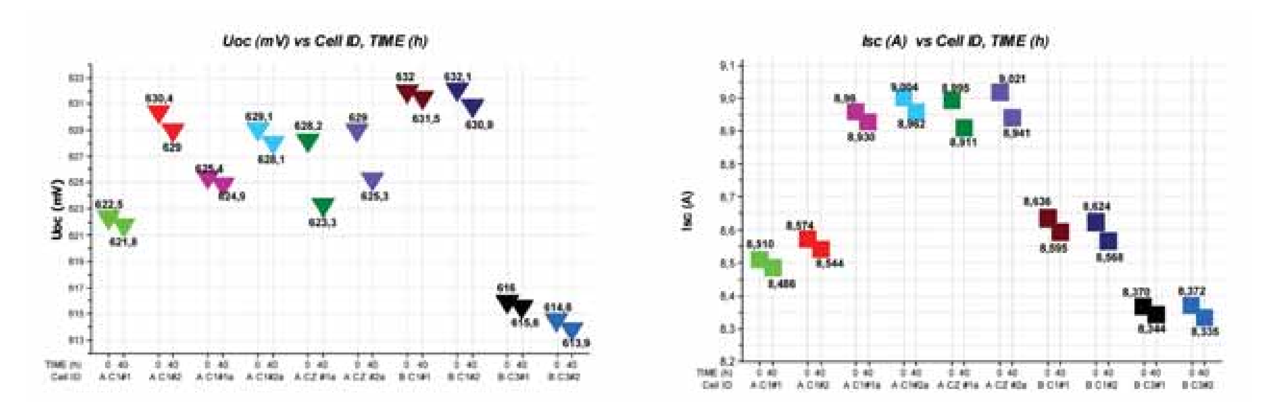


Figure 6. I_{sc} and V_{oc} before and after 40 hours' light-soaking for mono-cast material from suppliers A and B, and CZ material from supplier A.

the texturing impact on different mono-cast classes) and reflectance have recently been studied in more detail and new texturing chemistries to reduce the above-mentioned differences proposed [15–17].

Quantifying the LID effect for mono-cast materials

In order to confirm that the mono-cast classes and suppliers have no impact on the LID effect, groups of cells with similar bulk resistivities of 1.5–2.0Ωcm were chosen and measured ten times and the average values compared, as shown in Table 4. The LID test was performed for up to 40 hours, after which no further change in performance could be measured. No impacts of wafer supplier, quality or texturing on changes in I_{sc} and V_{oc} in response to LID were observed for mono-cast wafers, and no change in *FF* was observed for selected cells. As shown in Fig. 6, after the LID test, the efficiency levels for the best high-class mono-cast material were the same as for the CZ material.

Conclusion

For screen-printing technology, mono-cast material has significant potential for achieving an enhanced cell efficiency of more than 18%, an increase in V_{oc} of up to 9mV, and an increase in I_{sc} of more than 400mA. There are two areas of improvement: first, better bulk properties, with potential efficiency improvement of up to 0.6% absolute; and, second, an increase in efficiency of up to 0.8% absolute because of the possibility of performing anisotropic texturing for wafers with <100> crystal orientation, and further reducing reflectance.

There are new anisotropic texturing methods under development that would eliminate potential cosmetic issues with shiny areas where crystal orientation is not <100>. Improved bulk properties are a main factor for realizing gains in V_{oc}, because of the reduced number of grain and sub-grain boundaries. However, this is valid only for mono-cast material that does not have a greater number of dislocations compared to multicrystalline wafers. High I_{sc} performance comes partially from improved bulk properties, but more significantly from crystal orientation and reduced reflectance with anisotropic texturing. A V_{oc} of 632mV, an I_{sc} of above 9A, and an efficiency of 18.42% have been demonstrated. The low LID of mono-like material raises the level of performance of the best quality mono-cast cells to that of CZ mono cells.

The importance of a better classification has already been discussed [18–20] and is further emphasized in this work. However, further improvements in bulk material quality, and a higher share at the ingot level of premium-grade material with <100> crystal orientation, are essential, in order for mono-cast material suppliers to reach the challenging targets stated in the ITRPV [1].

Acknowledgement

The author would like to thank the Photovoltech team for their outstanding support: the process engineering and production group with production runs, G. Leys from the R&D group with pilot-scale runs, Dr. A. Ristow with the PLpix system set-up and image analysis, and Dr. J. Szlufcik for helpful discussions and reviewing this paper.

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About the Author

Milica Mrcarica received her MEngSc in photovoltaics from the University of New South Wales (UNSW), Australia. From 1995 to 2009 she was with BP Solar not only working on but also leading a wide range of engineering and R&D projects and technology scale-up. After that Milica was a process manager for screen-printing and LDSE technology with Roth&Rau R&D group. In 2011 she joined the Photovoltech R&D team, where she has been in charge of Si wafer evaluation and emitter development for standard and high-efficiency cell concepts.

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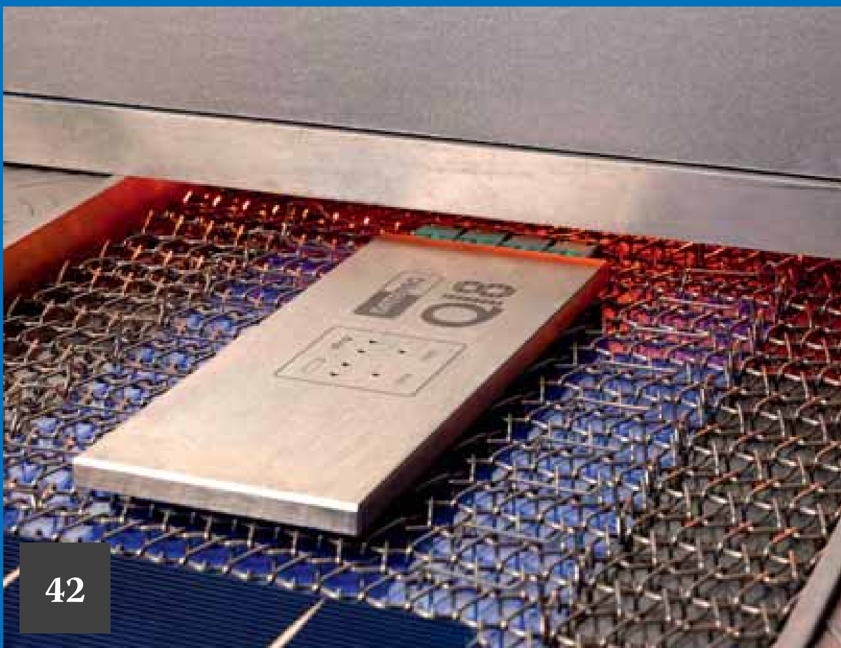
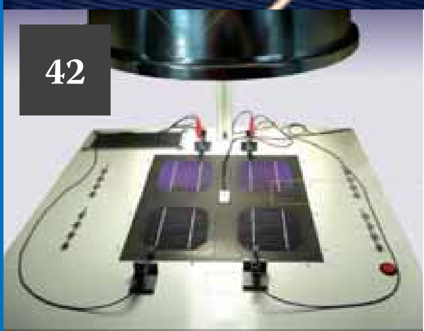
Cell Processing





News

US Energy Department announces US$12 million to bring solar technologies to market

The US Department of Energy (DOE) has announced the availability of US$12 million to accelerate solar energy innovation that could help reduce manufacturing and installation costs for homes, businesses and utilities. The new funding opportunity, which is part of the DOE's SunShot Incubator Program, expands on previous Solar Incubator rounds to support both hardware efficiency and soft cost reduction goals. The DOE said the funding will also help companies transition lab-scale ideas to prototype phases or move early-scale projects to commercial launch.

The DOE's SunShot Incubator Program helps launch start-ups and new business units within existing companies to speed up solar technology development and deployment in the United States.

Source: US Department of Energy

The US$12 million funding opportunity is part of the DOE's SunShot Incubator Program.

Solar cell records

Recombination loss improvements key to Panasonic HIT cell efficiency of 24.7%

Panansonic has produced an advanced version of its hybrid HIT solar cell with a record conversion efficiency of 24.7%, 0.8% higher than before. According to Panasonic, the record cell was produced in the lab, using a cell surface area of 101.8cm^2, with an n-type wafer thicknes of 98µm. Panasonic claimed that the 24.7% conversion efficiency, verified by Japan's National Institute of Advanced Industrial Science and Technology, is the highest rated of any crystalline silicon-based solar cell of 100 cm^2 and above the size used in practical production modules, based on an internal study of published data to date.

Sharp's triple-junction InGaAs solar cell reaches record 37.7% conversion efficiency

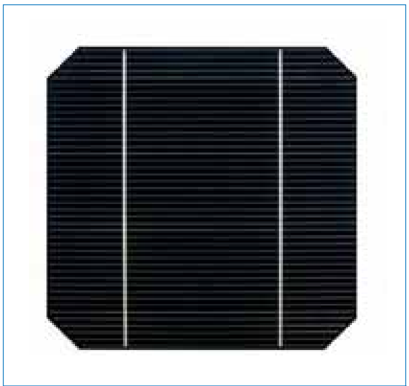
A CPV triple-junction compound solar cell developed and optimised by Sharp Corporation has been verified by Japan's National Institute of Advanced Industrial Science and Technology with a record conversion efficiency of 37.7%.

Sharp used an indium gallium arsenide combination as the bottom absorption layer while increasing the active area at the cell edges. The R&D program was supported by Japan's New Energy and Industrial Technology Development Organization. The device is targeted at CPV applications as well as space satellites and vehicles.

Research & Development

Kuwait University joins imec's silicon solar cell industrial affiliation program

Continuing Kuwait government efforts to build-out a renewable energy mix for the future, Kuwait University (KU) has teamed with European R&D centre, Imec on its silicon solar cell industrial affiliation program. Key work will revolve



Source: Panasonic

Panansonic has produced an advanced version of its hybrid HIT solar cell.

Source: imec

Kuwait University signed a long term collaboration agreement with Imec.

around Kuwait University researchers collaborating with imec researchers at imec's facilities in Leuven, Belgium that includes technology-modelling and simulation work, carried out by KU on advanced cell technologies.

News

ECN workshop declares MWT cell technology ready for mass production

A workshop held last week by ECN and Fraunhofer-ISE in Nemo, Amsterdam, has decreed that Metal Wrap Through (MWT) solar cell technology is ready for volume production among a number of PV manufacturers. PV manufacturers such as Canadian Solar, Yingli and Tianwei gave presentations on their latest developments with MWT technology during the two-day workshop, as well as leading R&D institutes such as ECN, Fraunhofer-ISE, ISFH and ISC Konstanz.

Order News Focus

Amtech wins solar cell diffusion equipment order worth US$5.3 million

An unidentified top tier solar company based in Asia has placed a US$5.3 million order with Tempress Systems, a subsidiary of Amtech for its solar cell diffusion processing tools. The company said the order was in relation to the customer planning to ramp a new multi-hundred megawatt capacity expansion plan. These systems are expected to ship within the next six months.

Intevac wins first production order for 'ENERGi' ion implant system

Specialist PV equipment manufacturer, Intevac has won its first production tool order for its continuous flux ion source 'ENERGi' system from an unidentified Asia-based solar cell manufacturer. The company said that the purchase order was a result of a successful evaluation process, typically employed with ion implant tools. The ENERGi system is claimed to offer improved performance over conventional POCl3 diffusion techniques by providing full amorphization that boost light response and simpler annealing by using solid phase epitaxial re-growth for better emitter formation.

Oxford Instruments system used for Black Si PV research at Anhalt University

The Anhalt University of Applied Sciences in Köthen, Germany, has purchased Oxford Instruments' PlasmaPro System100 ICP 65 tool. The university said the purchase would help it improve its research work. Key features of the PlasmaPro System100 includes an extended process temperature range from cryo to up to 400ºC.

Silvaco supplies modelling software for silicon nanowire solar cell work in Japan

Simulation software specialist Silvaco has won a competitive bid to supply its ATLAS device simulator technology to the Japanese funded FUTURE-PV project.

The company said the technology wuold be used by researchers at the Konagai and Miyajima Laboratory in the Tokyo Institute of Technology for supporting simulation experiments into silicon nanowire solar cells, especially in the field of understanding of quantum effects for future optimised solar cell structures. The work at the Fukushima Top-level United Center for Renewable Energy Research PhotoVoltaics Innovation (FUTURE-PV) project has been supported by the Japan Science and Technology Agency (JST). The ATLAS software provides 2D and 3D electrical, optical and thermal physical modelling.

Solar3D expects prototype 3D cell manufacturing partner in 2013

Three-dimensional solar cell developer Solar3D claims its next major step towards commercial introduction will be a manufactured prototype and a pilot production run sometime in 2013. Should these steps prove successful, the company has said that it would seek a manufacturing partner with the chance the technology could enter the commercial market by the end of 2013. The company does not expect to produce the cell itself as it believed it would not be able to compete with the leading low-cost PV manufacturers from China.

Business News Focus

Taiwan-based solar cell producers' shipments reach record levels in 2012

Taiwan-based solar cell producers generated record shipments of around 5.5GW in 2012, according to EnergyTrend, a market research division of research firm, TrendForce. However, the weak pricing environment due to overcapacity led to total revenue decline of between 25-50%. Leading the pack were Motech and Gintech, which were said to have both exceeded shipments of over 1GW in 2012. Only Motech had achieved such shipment levels in 2011, according to EnergyTrend. The four leading players, Motech, Gintech, Neo Solar Power and Solartech accounted for 67% of total shipments last year. However, Topcell, DelSolar and Tainergy were also successful in shipping around 300-350MW of solar cells each during 2012.

Neo Solar Power revises capital equipment spending plan

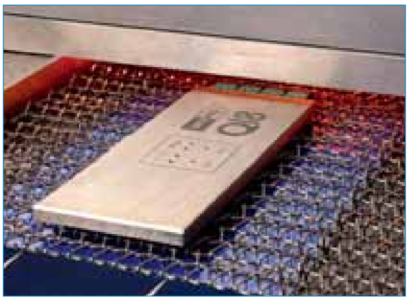
Taiwan-based solar cell manufacturer, Neo Solar Power (NSP) has revised down its capital equipment and materials spending plan as a result of the planned merger with DelSolar.

Source: Neo Solar Power

Neo Solar Power has revised down its previously planned capital equipment and materials spending plan.

Product Reviews

Datapaq



Datapaq temperature profiling system for contact paste drying

Product Outline: Datapaq has launched a tailored version of its SolarPaq temperature profiling system for contact paste drying processes.

Problem: A photovoltaic manufacturing line may contain up to three ovens that are used for drying the contact paste. Ensuring that all of these maintain maximum throughput and efficiency requires regular checking of the temperature profile. Incorrect drying will directly reduce process yield and the conversion efficiency of the final product.

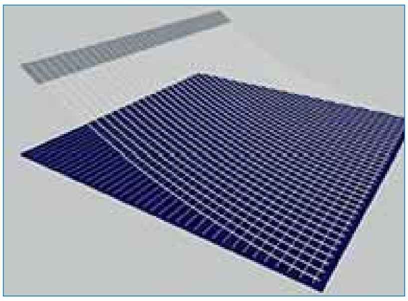
Solution: The application-tailored data logger is suitable for ovens with clearances as low as 10mm. The DQ1840 logger, a new model from the established Q18 series, withstands two to three minutes at up to 300°C without additional thermal protection. It is housed in a rugged stainless steel enclosure designed to reflect heat energy. Any absorbed energy slowly heats up the high-mass case protecting the electronics. The status indicators and buttons are all recessed to protect them from direct heat and minimize heat entry to the logger circuits. The four-channel data logger stores up to 55,000 readings per channel. It can take up to 20 readings per second, ensuring that even the smallest temperature deviations are captured.

Applications: Temperature profiling solution for contact paste drying processes.

Platform: The Datapaq Insight software provides the information required to optimize both product quality and production throughput at every stage in the PV manufacturing line. The temperature profiling system can travel through height restricted ovens monitoring cell temperatures at up to four points.

Availability: January 2013 onwards.

Meyer Burger



Meyer Burger offers 5% higher power output of solar cells

Product Outline: Meyer Burger's patented 'SmartWire Connection Technology' (SWCT) is designed to replace conventional silver-based busbars on solar cells using thin copper wires on both sides of the cell.

Problem: Heterojunction (HJT) cells are very sensitive to high temperatures above 180°C. Modules combining HJT cell technology with SWCT have achieved active area efficiencies of over 20%. The SWCT process is self-aligning and omits complicated ribbon lay-out on the contact surface of the cell.

Solution: The SWCT technology is claimed to significantly reduce the cost of production by eliminating the busbars on both sides of the cell and optimizing finger widths, thus reducing silver quantity by up to 80%. SWCT's fine copper wires reduce shading on the solar cell by 3% in comparison to cells with three busbars. Coupled with 2% lower series resistance, SWCT technology is claimed to increase the power output of a solar module by 5%. The round copper wires increase the amount of sunlight reflected onto the cells, resulting in SWCT-contacted modules beginning to produce electricity earlier in the day and stop producing electricity later in the day, which leads to an increased energy yield of about 10%.

Applications: SWCT is compatible with all crystalline silicon cell technologies: selective emitter, PERC and heterojunction (HJT) in both p- and n-type silicon cells.

Platform: Wafer thickness can be as low as 100µm. This very future-oriented technology can also be applied to the next generation of finger metallization technologies.

Availability: February 2013 onwards.

nTact

nTact's nRad low-cost slot die coating system is designed for low-cost R&D

Product Outline: nTact's nRad low-cost slot die coating system is based upon nTact's patented technology and engineered for use in R&D and pre-production environments. The nRad's simple yet flexible design provides accurate deposition of a wide range of materials for a variety of applications.

Problem: The PV industry is under constant pressure to reduce production costs effectively. nTact's highly efficient use of materials and low equipment cost of ownership presents a very attractive manufacturing alternative for the PV industry when compared to typical vapour deposition techniques and other technologies with poor material utilization.

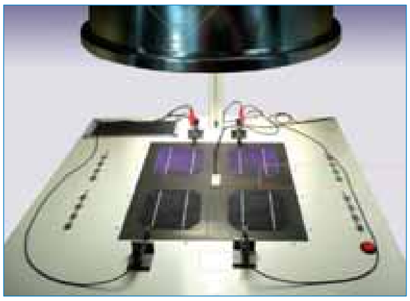
Solution: The slot die coating (extrusion coating) process is typically employed to deposit the process material over the entire substrate, with the exception of a small uncoated area (typically about 5-10mm wide) that is left around the perimeter of the substrate. For many customers, this full area coating meets their process objectives. However, for certain applications, it is desirable to have certain areas coated with the process material, while other areas are free of this material.

Applications: Provides accurate deposition of a wide range of materials for a variety of R&D applications.

Platform: The system is available in standard configurations for processing 150mm and 200mm square substrates, with options for 150mm and 200mm wafers or panels up to A4 (210x300mm) size.

Availability: Currently available.

PSE AG



PSE provides analysis of solar cells light-induced degradation

Product Outline: PSE AG has developed a new test stand, 'Degratest Labtool,' designed for the testing of light-induced degradation (LID) effect of silicon solar cells. The testing technology monitors and records degradation effects, and offers manufacturers and research institutions a fast and reliable tool for testing and developing solar cells. The LID test system was developed at ISC Constance.

Problem: LID of silicon solar cells reduces the minority carrier lifetime and therefore V_{oc} and I_{sc} on the solar cell level. Due to losses in V_{oc} and I_{sc} cell efficiency can decrease. Therefore investigations of the degradation behaviour are quite important to characterize given cells in industry or for research departments.

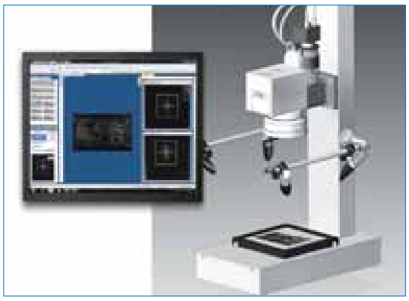
Solution: Degratest Labtool comes with an electronically controlled metal halide lamp, which produces artificial light close to the sun's spectrum. The heating of the test area is realized via a high-precision temperature controller and can be adjusted from 10°C to 220°C. To determine the LID effect, the test stand first generates a defined initial state of the cells to be tested (annealing). The test stand records all important parameters such as radiation, temperature, measured voltage and temperature-corrected voltage during the test and instantly creates a graph of the results.

Applications: Degratest Labtool can simultaneously test up to four solar cells with a maximum size of 160x160mm.

Platform: Spectral quality of the lamp: Class B. Maximum irradiance in test area: $1000Wm^{-2}$. All controls of the test stand are performed in a graphical user interface (GUI).

Availability: Currently available.

Scanlab



Scanlab's 'SCANalign' vision system tailored to solar cell processing

Product Outline: Scanlab has broadened its offering with 'SCANalign,' a vision system tailored specifically to the demands of laser processing steps used in solar cell fabrication steps.

Problem: With the SCANalign vision system, users can realize high-precision laser processing in low-precision environments.

Solution: The system automatically recognizes and locates fiducial markers or other features on workpieces, so that the laser beam can be very precisely positioned with respect to these fiducials. The result of the laser processing is thus more precise than any part or mechanical fixture in the machine itself. In addition, the vision system allows calibrating the working field and checking the result of the laser process. The SCANalign vision system takes pictures through the laser scan head and is easy to use and set up. By observing the work piece through the scan head, the system effectively corresponds to a camera with over 100 million pixels. This yields high precision for measuring features across the complete working field. Precision is higher and the working distance larger than in typical vision systems.

Applications: Laser processing steps used in solar cell fabrication steps.

Platform: The SCANalign system consists of a software package with an intuitive graphical user interface, a camera, a camera adapter, an illumination system and a high-precision calibration plate. A stand-alone and an OEM bundle will be made available. The vision system interfaces with Scanlab's laserDESK software. Training, installation and support, including in the domain of illumination, are provided.

Availability: Currently available.

SoLayTec

SoLayTec's 'InPassion' ALD system offers mass-produced Al_2O_3 deposition

Product Outline: SoLayTec has introduced its 'InPassion' ALD (atomic layer deposition) tool for depositing Al_2O_3 in mass production. Al_2O_3 is well known in the PV community for highly effective surface passivation properties and negative fixed charge density, which is required for thinner wafer usage. The InPassion ALD tool is capable of processing up to 4,500wph.

Problem: The next generation of silicon-based solar cells aims at efficiencies of 20% and above. To achieve this goal using ever-thinner silicon wafers, a highly effective surface passivation of the cell (front and rear) is required.

Solution: Al_2O_3 ALD quality and uniformity wafer-to-wafer is claimed to be <4% and the wrap around is less than 1mm. The passivation of low-resistivity p-type silicon by the negative charge dielectric Al_2O_3 is claimed to provide a conversion efficiency of 20.6%. Depending on the number of modules selected (6 or 10) the nominal throughput can differ between 2,160wph and 3,600wph, based on 10nm of Al_2O_3.

Applications: Front- and rear-side Al_2O_3 passivation for both p- and n-type cells.

Platform: The InPassion ALD systems are delivered inclusive of automation, gas cabinet and abatement system. The wafers are floating on air from left to right and pass the injector head without physical contact. It is at this point where the layer is created by spatial ALD under atmospheric pressure. The deposition rate is 1.0nm/second per module

Availability: Currently available.

i-PERC technology enables Si solar cell efficiencies beyond 20%

Filip Duerinckx, **Emanuele Cornagliotti**, **Victor Prajapati**, **Angel Uruena**, **Patrick Choulat**, **Philip Pieters** & **Jef Poortmans**, imec, Leuven, Belgium

ABSTRACT

A cost-effective and industrial version of the well-known passivated-emitter and rear cell (PERC) concept has been developed by imec. The imec i-PERC technology comprises a large-area p-type monocrystalline Si solar cell with, on its front, a homogeneous emitter, a thin thermal oxide layer and fine-line Ag screen-printed contacts; on its rear, the cell has a chemically polished surface, low-cost rear dielectric stack layers and local Al contacts. Yielding certified efficiencies of up to 20% and fill factors of 80%, these cells clearly outperform aluminium back-surface field (Al-BSF) cells. During the development stages, process complexity and additional tool investment were kept to a minimum. It is therefore believed that this technology can be picked up by companies in a straightforward way as the next-generation industrial solar cell technology.

Introduction

Today's workhorse of the Si PV industry is the Al-BSF Si solar cell, a cell with screen-printed full Al back-surface field and screen-printed, fired-through Ag contacts on the front. When produced from large-area wafers, these cells demonstrate efficiencies typically in the range of 18.3–18.8%, but the technology offers little room for further improvement. Issues such as wafer bowing, low internal reflectance and limited surface passivation restrict the production of cheap and highly efficient thin Si solar cells. In times of aggressive competition in the PV sector, the adoption of advanced solar cell concepts can however be highly beneficial from an economic perspective. Besides yielding higher efficiencies, such new technology must allow mass production of solar cells in a cost-effective way, with only limited additional investment.

Providing high conversion efficiency and limited Si consumption, the passivated-emitter and rear cell (PERC) concept shows great promise for one such next-generation industrial solar cell. This technology was pioneered by imec in 2005; since then, the first cells have emerged in industrial solar cell production, and record solar module efficiencies have been reported [1]. In order to promote widespread acceptance, imec has further optimized the process steps of this solar cell concept. The result is a highly efficient, cost-effective and industrial version, referred to as the 'i-PERC' solar cell. With this technology, the above-mentioned disadvantages of Al-BSF cells have been addressed, and thinner – hence cheaper – wafers can be used for production. i-PERC cells demonstrate fill factors of up to 80% and certified best efficiencies of up to 20.04%. Using this technology, a company can significantly increase the capacity of its production line in terms of W_p and reduce the cost per W_p. Moreover, the processing and capital expense differences in manufacturing i-PERC cells have been kept to a minimum. This paper presents the key elements of cost-effective i-PERC technology in terms of process step optimization and cell results.

"i-PERC cells demonstrate fill factors of up to 80% and certified best efficiencies of up to 20.04%."

i-PERC technology

i-PERC technology comprises a large-area p-type monocrystalline Si solar cell with a homogeneous emitter, fine-line Ag screen-printed front contacts and local rear contacts. Local rear contacts are formed by laser ablation of the dielectric layer prior to the Al deposition and the firing step. A generic process sequence for fabricating i-PERC-type cells is shown in Fig. 1 (right). Compared to the Al-BSF sequence, shown in Fig. 1 (left), i-PERC technology involves four new processing steps: (1) rear-surface polishing, (2) low-temperature thermal oxidation, (3) rear plasma-enhanced chemical vapour deposition (PECVD) of SiO_x/SiN_x, and (4) laser ablation of rear dielectrics. Cells produced this way have a higher efficiency potential than Al-BSF solar cells. To exploit that potential, it is equally important to develop a simple and cost-effective process flow.

In the next section it will be shown how the optimization of these key process steps leads to cost-effective solar cells with improved efficiencies. The manufacturing

Figure 1. Generic process sequences: Al-BSF (left) and i-PERC (right).


SCHMID
Let the Sun shine. Catch the Power.
Silver-free cell backside saves 6 US cent/wafer and
increases efficiency by 0.2%abs.
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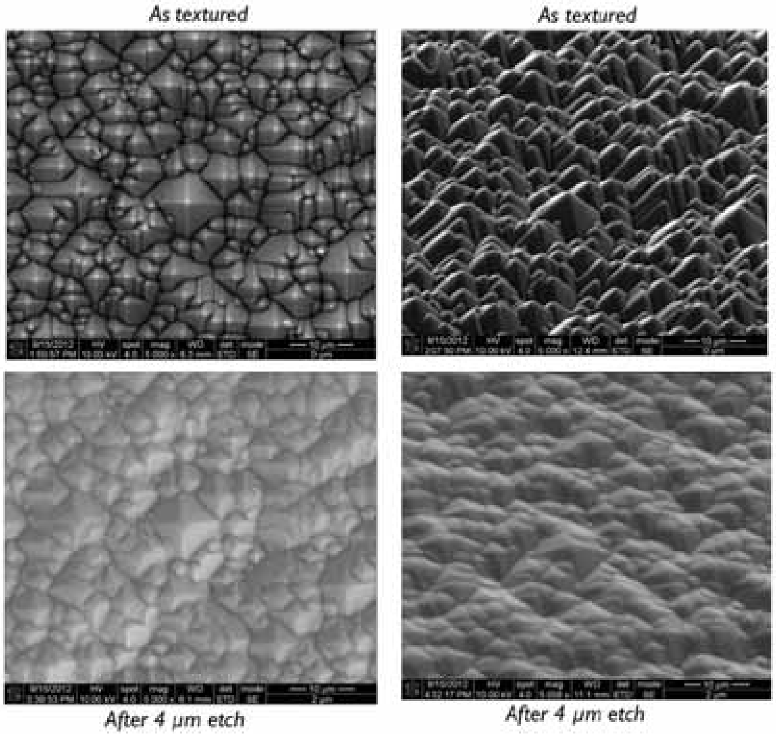


Figure 2. Scanning electron microscope (SEM) images after random pyramid texturing (top) and after a 4μm polishing etch (bottom). The view from above is shown on the left and with a 45° tilt on the right.

processes have been developed within imec's state-of-the-art Si solar cell pre-pilot line using industrially compatible equipment.

Process step optimizations

Rear-surface polishing – key to improved efficiency

Unlike for Al-BSF solar cells, the rear-surface topography plays an important role in the fabrication of PERC-type solar cells: it affects, to a large extent, surface recombination, light trapping and the local rear-contact formation process. As wafers become thinner and thinner, the effects of rear-surface conditioning will become ever more pronounced.

Take surface recombination as an example. When using random pyramid textured surfaces, a high degree of unwanted electrical recombination at the surfaces is observed. An extra polishing step to reduce the surface roughness significantly improves the electrical properties of the surface. But to what extent does this rear polishing step have an effect on light-trapping performance and contact formation? And what is the impact on process complexity and processing cost? To answer these questions, the optimum rear polishing process has been determined that, overall, leads to the best results, keeping in mind that, in an effort to minimize the material costs, the amount of Si consumption during the polishing step should be kept as low as possible.

The rear polishing step is applied to the textured rear surfaces by means of an in-line single-side wet-etch tool. An acidic solution, based on a HF/HNO_3 mixture, is used for the chemical etching. A progressive smoothening of the surface is observed as chemical etching is applied to the textured surface (Fig. 2). As the etch depth is increased, the residual roughness of the surface is reduced. Cells with different degrees of rear roughness were fabricated to study the impact of the polishing step on light trapping, surface recombination and contact formation.

The lowest values for the open-circuit voltage (V_{oc}), fill factor (*FF*) and short-circuit current density (J_{sc}) were observed in the case of the rear textured surfaces. With increasing Si etch depth, rear-surface recombination velocity decreases and, in general, V_{oc} increases. However, the V_{oc} correlation is not necessarily monotonic. As the roughness of the rear surface is modified, the dynamics of the local contact formation can differ substantially, which can influence the quality of the local Al-BSF, thereby influencing V_{oc}. This is not surprising, as mass exchange between Al and Si takes place all over the rear surface. It was observed for instance that, with Al sputtering metallization, V_{oc} can decrease as the polishing etch depth is increased above a value of 5–6μm. In addition, light-trapping performance was seen to improve as pyramids became smoothened. To maximize light trapping, however, a full planarization of the rear surface was not necessary [2]. This is reflected in the plot of J_{sc} vs. etch depth shown in Fig. 3 (note that the reduction in J_{sc} for etch depths greater than 5μm is only partially attributable to the reduction in total thickness).

> "A moderate smoothening, corresponding to a Si etch depth of around 5–6μm, results in the best cell performance."

Overall, it can be concluded that a moderate smoothening, corresponding to a Si etch depth of around 5–6μm, results in the best cell performance. When combined with other improvements, cell efficiencies above 20% can be achieved. On the other hand, a complete planarization of the rear surface can be detrimental, besides being uneconomical. While surface recombination generally benefits from a

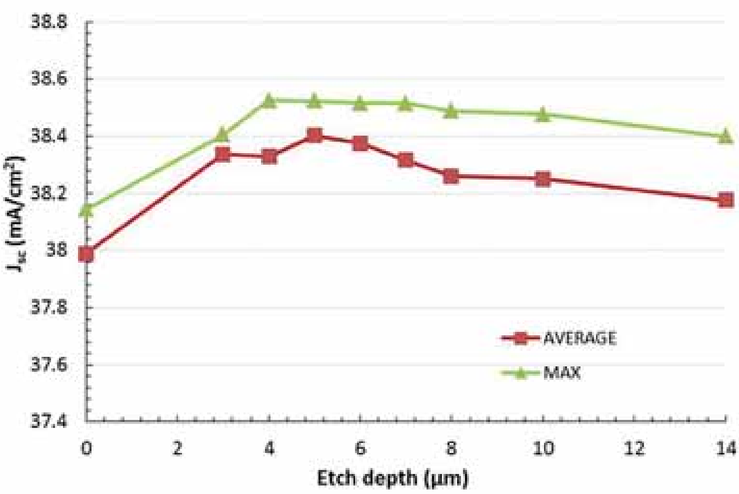


Figure 3. Short-circuit current density (J_{sc}) of i-PERC cells vs. polishing etch depth.

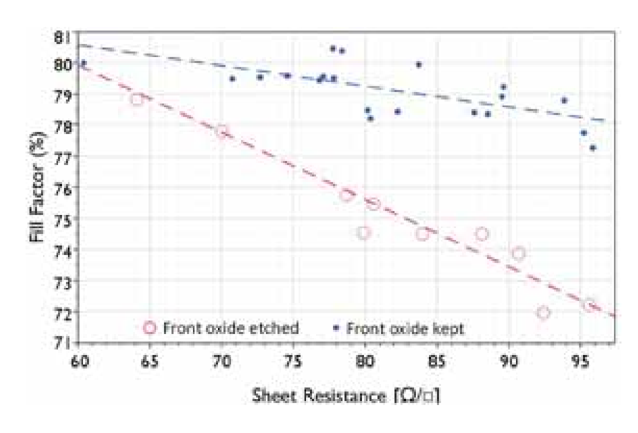


Figure 4. Fill factor vs. sheet resistance for cells with and without thermal oxide.

flat rear surface, light absorption and contact formation are more effective with moderate smoothening.

Thermal oxidation on the front – key to improved fill factor and reduced Ag consumption

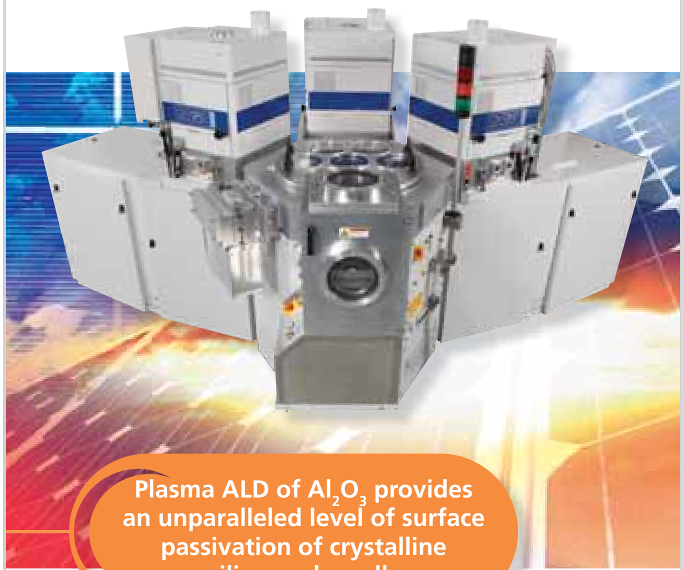
An easily implementable way of increasing cell efficiency without incurring too much cost is to introduce thermal oxidation. Thermal oxide is well known to the microelectronics industry as one of the best dielectrics for passivating Si surfaces. A thermal oxidation step has the advantage that surface cleaning and passivation happen to both the front and rear surfaces at the same time. Surprisingly, it was observed that the thermal oxide as a passivation layer on the front and rear surfaces leads to, on the front, a significant *FF* improvement for screen-printed Ag contact formation (Fig. 4). This enhancement was observed for a homogeneous emitter solar cell subjected to a thin thermal oxidation performed at 800°C, before further passivation and subsequent metallization [3].

Further investigations have revealed that this gain in *FF* is mainly due to the contact resistance improvement in conjunction with enhanced passivation. During the low-temperature oxidation step, electrically inactive phosphorus is incorporated from the topmost emitter region into the growing oxide. These high P concentrations in the oxide film help the contact formation for screen-printed Ag contacts. They allow homogeneously diffused, high-resistance emitters (~80–90Ω/sq.) to be contacted with industrially available pastes, with *FF* values exceeding 79%.

Another advantage of the improved contact resistance is the possibility of using less Ag without compromising the cell's efficiency. Such a reduced Ag consumption is highly desirable, as the Ag paste's share of the total cell processing cost has dramatically increased in recent years. Emitters with high sheet resistance require the effective finger width of the Ag to be reduced and the number of fingers to be increased. When this is done properly, modern Ag pastes allow excellent conductivity to be obtained while a significant reduction in overall Ag consumption is realized. The authors believe that a simple processing sequence of this type for emitter and contact formation has cost advantages over approaches that make use of, for example, selective emitters. The latter involve a higher number of processing steps and require a higher degree of accuracy during the metallization step.

Rear-surface passivation – key to enhanced efficiency

The evolution towards thinner, and hence more sustainable, Si solar cells comes with an inherent decrease in efficiency. This decrease is due to the recombination of minority charge carriers at the surfaces and interfaces, an effect that begins to play a bigger role in thinner cells. Yet, as the wafer thickness decreases, it is possible to maintain cell efficiency with better surface passivation than with full Al-BSF. Rear passivation by dielectric layers is therefore essential in the i-PERC process flow. Besides passivation, the dielectric layers have additional functions: they have to serve as a rear reflector



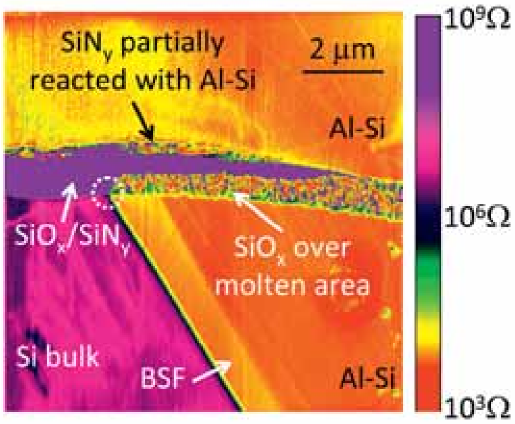


Figure 5. SSRM analysis of a local contact point, showing local BSF, Al-Si eutectic, dielectrics and possible reactions of the dielectrics with Al during the firing process.

Figure 6. A solar cell made using imec's i-PERC technology.

Description	J_{sc} [mA/cm^2]	V_{oc} [mV]	*FF* [%]	*Eff* [%]
125mm Cz-Si, SCP Ag	38.6	662.8	78.3	20.0
156mm Cz-Si, SCP Ag	38.2	650.1	79.7	19.8

Table 1. Solar cell performance for two large-area i-PERC cells, as confirmed by ISE CalLab.

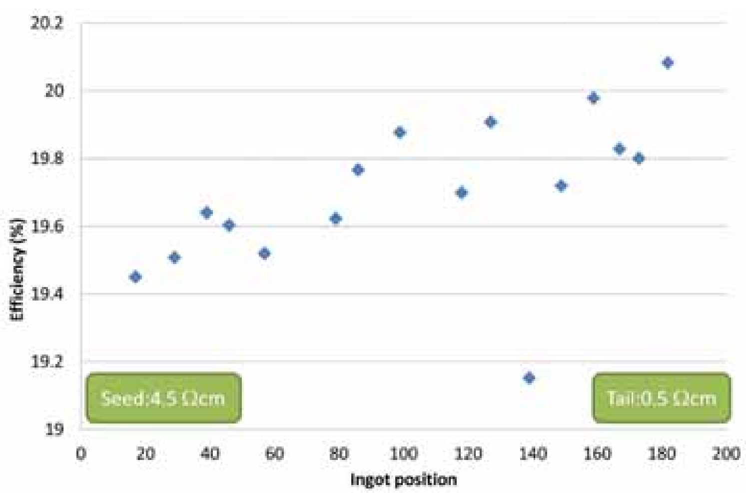


Figure 7. Efficiency distribution across a Ga-doped ingot for the i-PERC screen-printing process applied to Si wafers.

and prevent unwanted contact spiking at areas where the layers have not been laser-opened for rear-contact formation. Optimizing the dielectric stack design for these purposes should additionally take into account the need for low cost of ownership in order to be industrially applicable.

One of the routes followed by imec is to apply the thermal oxide layer for rear-surface passivation purposes as well. This thermal oxide layer does not have to be thicker than a few nanometres to be beneficial and serve several purposes. The overall rear passivation stack should, in the authors' view, also comprise a low-cost Si oxide layer of thickness greater than 100nm that serves, for optical purposes, as the rear reflector, and reduces the negative impact from the unwanted interaction with Al during rear-contact formation. Finally, the rear dielectric stack is covered with a SiN_x layer. During contact firing, this layer prevents the Al rear from spiking through the dielectric stack and from consuming SiO_x in unwanted regions [4]. PECVD is used to deposit both the SiO_x layer and the SiN_x layer.

Rear-surface metallization – trade off between improved fill factor and open-circuit voltage.

In i-PERC technology, the local rear Al contacts are formed by opening the dielectric layers with laser ablation, followed by a deposition of the Al layer over the whole rear surface and subsequent annealing. Typically, the laser openings follow a dot pattern with a specified pitch. Initially, screen printing was used to deposit the Al layer on the rear surface. On the whole, this metallization process flow is fairly simple. To further enhance cell performance, imec is examining different ways of depositing Al. Screen printing of Al-based pastes, and methods based on physical vapour deposition (PVD), such as sputtering, e-beam evaporation and thermal evaporation, are all being examined. It is possible to obtain outstanding solar cell performance with these two technologies: so far, they have both led to excellent *FF* values (even exceeding 80%), while PVD depositions allow the best V_{oc} values (of up to 664mV) to be realized. The use of PVD to deposit Al can result in large cost savings in respect of materials, but will lead to a higher investment cost in terms of equipment.

The optimized rear-contact pattern strongly depends on (i) the base resistivity of the wafer, (ii) the laser-ablated dot size, (iii) the nature of the metal layer, and (iv) the annealing temperature to form the contacts. At imec the rear-contact formation has been analyzed by using in situ microscopy. Although the analysis is still ongoing, these measurements, in combination with a cross-sectional scanning spreading resistance microscopy

(SSRM) analysis, have already revealed a lot of information about the phenomena occurring during rear-contact formation (Fig. 5). The measurements will help to further improve the process flow for rear-surface metallization [4].

Impact of process optimization on cell efficiency, process complexity and cost

By using the optimized process steps discussed earlier, it has been possible to fabricate solar cells that considerably outperform Al-BSF solar cells. The best cell made from 125mm Cz-Si shows a solar efficiency of 20.0%; the best cell made from large-area 156mm Cz-Si has an efficiency of 19.8% (Fig. 6 and Table 1). Both results have been confirmed by ISE CalLab. More recently fabricated cells from 125mm Si well exceed the 20% efficiency mark. Fill factors of 80% have been achieved for screen-printed solar cells with low-cost rear dielectric stack layers.

The improved i-PERC screen-printing process has been applied to many different wafers. In Fig. 7 the efficiency distribution is shown for Si wafers taken across a Ga-doped ingot from seed side to tail side. The efficiency on the seed side is lower, mainly because of a higher base resistivity, which affects the internal resistance and hence the fill factor. This difference in base resistivity is a consequence of the low segregation coefficient of Ga in Si. Ideally, for these types of wafer, the contact pitch needs to be adapted to changes in resistivity, which was not done for this particular experiment. An advantage of these cells is that they do not suffer at all from light-induced degradation (LID).

> "The increase in cell efficiency may be up to 1.5% absolute compared with conventional Al-BSF cells."

Depending on the case, the increase in cell efficiency may be up to 1.5% absolute compared with conventional Al-BSF cells. Of course, this higher efficiency level comes at the cost of an increased process complexity. Although the processing and capital expense differences have been kept to a minimum, four extra tools have to be anticipated for the additional process steps: an in-line polishing wet bench, thermal oxidation equipment, a PECVD system for rear dielectric deposition (which can potentially be combined with front antireflection coating (ARC) deposition) and a laser platform for ablation. However, because of the significant increase in efficiency, the capacity of a company's production line in terms of W_p will largely increase and the cost per W_p will fall. A payback of the additional investments has been calculated to happen in an acceptable timeframe. It is therefore envisaged that the new i-PERC technology could be picked up by industrial companies in a straightforward way with only a limited investment. And, besides the increase in efficiency, it should not be forgotten that the i-PERC process allows the use of thinner and hence cheaper wafers, while maintaining the high efficiency level and production yield.

Conclusion

Key improvements to imec's PERC technology have been presented which allow the manufacture of large-area solar cells with efficiencies of up to 20%. This is a significant leap in efficiency compared to traditional Al-BSF solar cells. The improved cell performance is a result of a polishing of the textured rear surface, a thermal oxidation of the front and rear surfaces, a rear passivation with a dielectric stack and an improved rear metallization process. Additional investment needed to manufacture these optimized cells has been kept to a minimum. The real advantage for industrial companies is a significant decrease in the cost per W_p, allowing the payback of additional investment within a reasonable time frame.

> "The real advantage for industrial companies is a significant decrease in the cost per W_p, allowing the payback of additional investment within a reasonable time frame."

The results were achieved within imec's Si solar cell industrial affiliation programme (IIAP), a multi-partner R&D programme that explores and develops advanced process technologies aimed at sharply reducing Si use while increasing cell efficiency, and hence substantially lowering the cost per W_p even further. Industrial partners who wish to integrate innovative processes into their solar cell production are welcome to join imec's R&D programme.

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Achieving higher efficiencies with a low-cost etch for in-line-diffused silicon wafer cells

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ABSTRACT

Emitter formation is one of the most critical processes in the fabrication of silicon wafer solar cells. The process for standard emitter formation adopted in the photovoltaic industry is tube-based diffusion, using phosphorus oxychloride as the dopant source. A potentially low-cost alternative that typically results in lower solar cell efficiencies is in-line diffusion, using phosphoric acid as the dopant source. The Solar Energy Research Institute of Singapore (SERIS) recently developed a technique called the 'SERIS etch', a non-acidic etch-back process technology that provides a controllable, uniform and substantially conformal etch-back suitable for solar cell processing. By using the SERIS etch, efficiencies of up to 18.7% have been demonstrated for homogeneous-emitter silicon wafer cells; a 0.4%$_{abs}$ efficiency improvement has also been achieved for a unique selective-emitter approach exploiting this novel etch. All work was carried out on industrial-grade p-type Cz wafers with conventional screen-printed metallization and a full-area aluminium back-surface field (Al-BSF). With Al local BSF (LBSF) homogeneous-emitter solar cells, efficiencies of 19.0% were achieved using in-line emitter diffusion and the SERIS etch, a 0.7%$_{abs}$ efficiency increase over the baseline efficiency at the time. To the authors' knowledge, these are the highest solar cell efficiencies ever reported for in-line-diffused silicon solar cells. Moreover, the SERIS etch is a cost-effective alternative to generating pyramid-textured surfaces without using conventional metal-assisted silicon-etching processes.

Introduction

The PV industry is currently aiming for high-efficiency Si solar cells. Any gains that manufacturers can make in converting light to electricity are directly translated into better margins, provided it can be done with a minimal investment. Increasing the efficiency by 0.1%$_{abs}$ means profit margins will go up by US$200k for each 100MW of production, if no investment is required. Accordingly, an improvement from 0.4%$_{abs}$ to 0.7%$_{abs}$ in efficiency can result in a US$1 million improvement in margin. At SERIS an inexpensive way has been found for increasing the efficiency of solar cells by applying a non-acid, cheap chemical as the silicon etch after creating the emitter on a monocrystalline cell. This process has also been applied to multicrystalline cells and generates similar efficiency gains of 0.3%$_{abs}$ to 0.6%$_{abs}$.

In the PV industry a batch-based tube diffusion with a high-purity phosphorus oxychloride ($POCl_3$) liquid dopant source is the standard for the formation of the n-type emitter. Tube diffusion is a highly reliable process, which results in high-quality emitters that can be used for high-efficiency Si wafer solar cells. Complex wafer handling and automation, however, are necessary for loading the wafers into and unloading them out of the quartz carriers, and a relatively long process time per batch is required.

> "In-line diffusion offers a cost-effective alternative for forming the emitter of Si wafer solar cells."

In-line diffusion offers a cost-effective alternative for forming the emitter of Si wafer solar cells. In contrast to batch-based processing, in-line processing enables continuous transport of the Si wafers throughout the processing chain using belts and rollers. The employment of simple 'belt-to-belt' handovers between process steps largely eliminates complicated wafer loading and unloading; hence, large cost savings in automation can be realized by in-line processing. The use of in-line processing is well established and has demonstrated its benefits in areas such as chemical processing (texturing, etching, etc.), anti-reflection coating (ARC) deposition by plasma-enhanced chemical vapour deposition (PECVD) and screen-printed metallization. Thus, emitter formation by tube diffusion is often the only batch-based process interrupting an in-line process flow.

A multi-lane belt or roller in-line-diffusion furnace allows high throughput per tool, with an end-to-end processing time of less than 30 minutes when phosphoric acid (H_3PO_4) is applied as the phosphorus (P) dopant source. However, lower-grade chemical precursors, the short diffusion time, the open-ended design of the furnace, and the metal belt are potential disadvantages of in-line diffusion. As a result, in-line-diffused emitter Si solar cells typically achieve lower PV efficiencies compared with tube-diffused solar cells.

The short duration of the in-line-diffusion process results in a dead surface layer (due to surface contaminants and a high dopant concentration at the surface) and a very shallow junction, which limits the open-circuit voltage (V_{oc}) and the efficiency of in-line-diffused emitter solar cells. In-line-diffusion is commonly performed on both sides of the Si wafer to minimize back-surface contamination from the metallic conveyor belt and this allows additional P gettering. Nevertheless, rod-like structures of silicon phosphide precipitates are typically observed on in-line-diffused emitter surfaces, even after removal of the phosphosilicate glass (PSG) layer with a diluted hydrofluoric acid (HF) solution. Horzel et al. [1] proposed that these structures are formed during rapid cooling of the dopant solution (H_3PO_4 and solvents), involving very high P concentration above the solid solubility limit of P in Si. Thus, in order to achieve high efficiencies using in-line diffusion, a reduction or complete removal of this heavily doped dead layer and surface contaminants is necessary.

SERIS etch

Based on additional surface cleans after in-line diffusion, various cleaning or etching processes have been developed to remove the above-mentioned dead layer and surface contaminants. These processes generally provide a shallow etch-back of the anomalously doped in-line-diffused emitter surface region. Voyer et al. [2] used a mixed solution of nitric acid (HNO_3) and HF on an in-line-diffused emitter surface, as well as other processes such as the 'ECN Clean' [3], 'extended surface clean' [4], and so on. SERIS has developed its own HF-free non-acidic etch-back solution – the 'SERIS etch' [5] – which offers unique advantages compared with the current state-of-the-art techniques; these advantages are discussed in the next sections.

Uniform etching

Laterally uniform dopant diffusions, which are contactable and can result in a good blue response (e.g. because of a low recombination or the absence of a dead surface layer), are extremely important for fabricating high-efficiency Si wafer solar cells. The uniformity of the emitter is qualified by the sheet resistance (R_{sq}) as well as the diffusion depth and the surface dopant concentration. Generally, a high emitter R_{sq} is preferred with a low surface dopant concentration in order to reduce surface recombination losses. However, the formation of these so-called 'shallow emitters' is quite challenging, especially using tube diffusion, and typically these high-R_{sq} tube-diffused emitters suffer a high non-uniformity that affects the performance of the final solar cell device.

Deeper diffusions are typically much more uniform and have the additional advantage of advanced P gettering, thereby improving the bulk material quality. Thus, by using a combination of a deep diffusion with a heavy uniform etch-back, all advantages can be exploited at once, resulting in potentially higher solar cell efficiency.

A low-cost alternative to tube diffusion is in-line diffusion, which features an excellent uniformity because of the direct deposition of the dopants. However, an emitter etch-back is compulsory for in-line-diffused emitters, owing to the formation of P precipitates on the diffused surface [1]. It is essential that this etch-back does not compromise the uniformity of the initial emitter.

"The SERIS etch enables a much deeper and uniform etch-back to be achieved, to maximize the advantages of dead layer removal and low surface concentration."

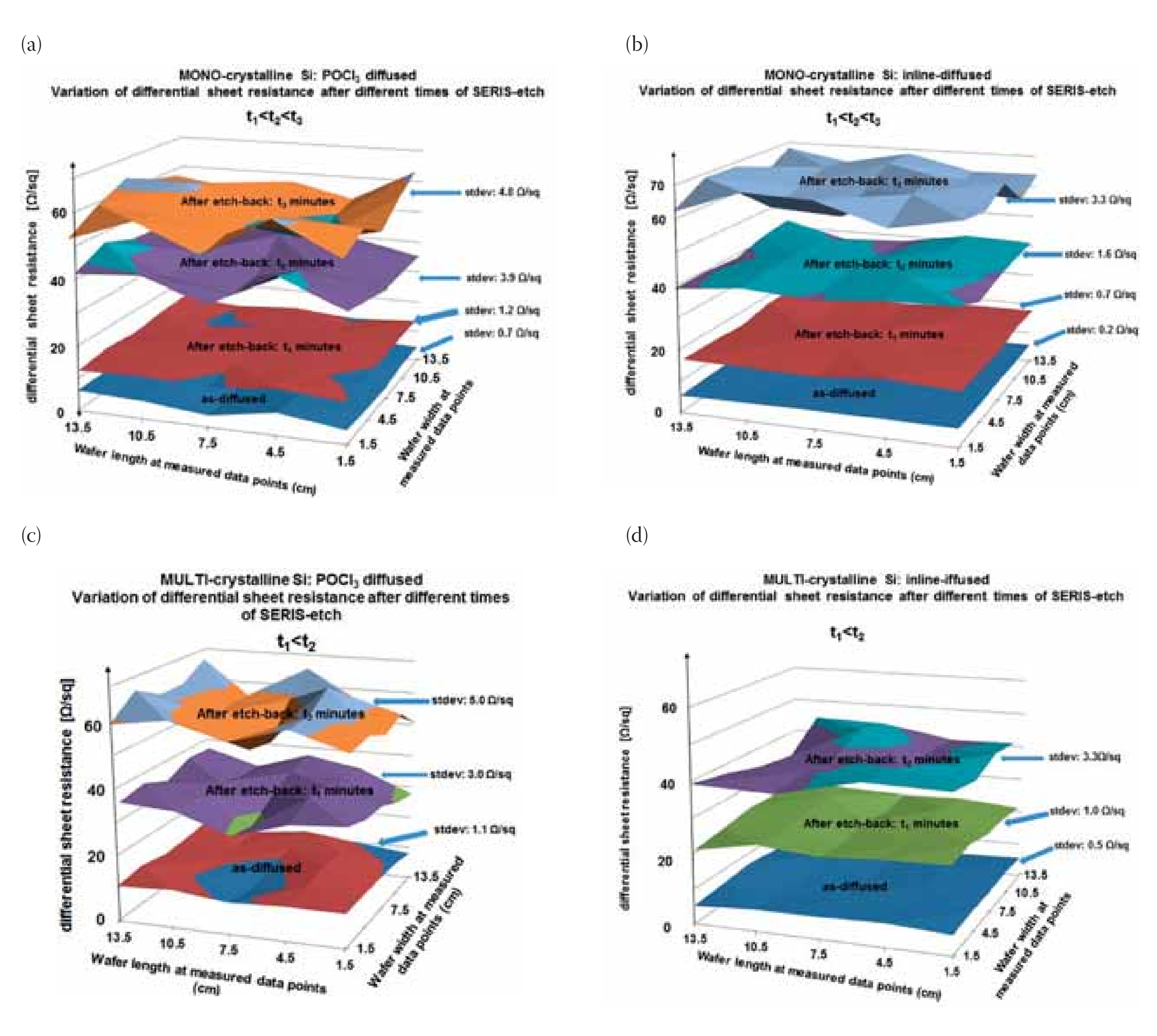
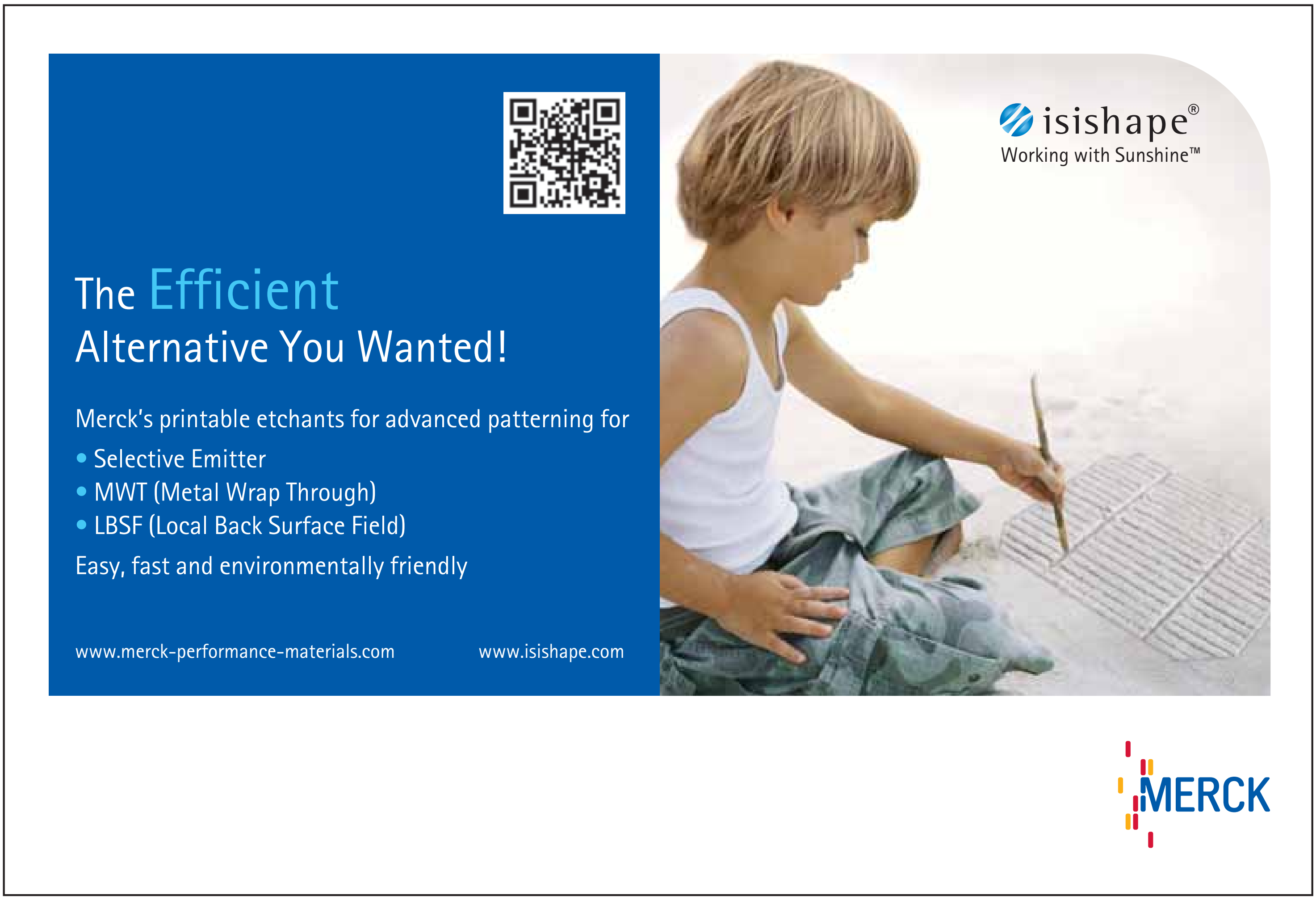


Figure 1. Variation of differential R_{sq} before and after different durations of etch-back using the SERIS etch: (a) tube-diffused ($POCl_3$) pyramid-textured mono-Si wafers (as-diffused emitter R_{sq} ~50Ω/sq); (b) in-line-diffused pyramid-textured mono-Si wafers (as-diffused emitter R_{sq} ~45Ω/sq); (c) tube-diffused multi-Si wafers (as-diffused emitter R_{sq} ~50Ω/sq); (d) in-line-diffused multi-Si wafers (as-diffused emitter R_{sq} ~45Ω/sq).



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The SERIS etch enables a much deeper and uniform etch-back to be achieved, to maximize the advantages of dead layer removal and low surface concentration. The average of the variation of R_{sq} before and after the etch-back (defined here as the 'differential sheet resistance') is shown in Fig. 1 for alkaline-textured monocrystalline silicon (mono-Si) as well as acidic-textured multicrystalline silicon (multi-Si) wafers, with emitters formed using both tube (Fig. 1(a) and Fig. 1(c)) and in-line (Fig. 1(b) and Fig. 1(d)) diffusion. The sample wafers are in-line-diffused; after PSG removal in dilute HF solution, the diffused wafers are etched in the SERIS etch solution for different lengths of time. The spatially resolved R_{sq} of the emitter is measured using standard four-point probe (4PP) measurements. As can be seen, the uniformity of the etch-back on the tube-diffused and in-line-diffused emitters is comparable, with a slightly higher non-uniformity on multi-Si wafers. Typically, etch-back processes show strongly increasing non-uniformity for deeper etch-backs. In contrast to typical etch-back processes, the SERIS etch-back maintains an excellent uniformity of ≤ 5Ω/sq standard deviation (stdev) in R_{sq}, even for deep etch-backs that increase R_{sq} by more than 50Ω/sq.

Conformal etching

In any etch-back process, retaining the morphology of the original surface is an important consideration, and this is especially challenging for extended etch-backs. For the conventional etch-back process using $HF\text{-}HNO_3$, conformal etching is severely hampered by the non-uniform growth of a porous Si layer on the textured surface. For pyramidal Si surfaces, porous Si growth is greatest along the pyramid tips, and the pyramids are thus deformed after the etch-back process [6]. The surface reflectance therefore increases, which affects the efficiency of the final solar cell. However, as can be seen in Fig. 2, when using the SERIS etch there is no significant deformation of pyramidal structure, even after an extremely deep etch-back from R_{sq} of ~45Ω/sq to ~100Ω/sq (a typical targeted R_{sq} value for selective emitter in non-metalized cell areas). This can be explained by the chemistry of the SERIS etch: porous Si formation is not required, as the solution *directly* etches crystalline silicon. This unique etching chemistry thus allows extremely conformal etching of Si surfaces, including n-type and p-type emitters.

Surface cleaning

Tube diffusion uses high-purity $POCl_3$ as the P dopant source; during diffusion, only $POCl_3$ vapours come into close contact with the Si wafer inside the closed tube, along with high-purity oxygen and nitrogen gases. However, in-line diffusion uses a H_3PO_4-based solution as the P dopant source, which becomes physically deposited on the Si wafer in the pre-diffusion stage and then undergoes the diffusion process in the air atmosphere on a metallic conveyor belt. Hence, it is not surprising that the PSG formed during in-line diffusion contains additional surface contaminants, which are significantly more difficult to remove than the PSG formed during tube diffusion.

The residual surface contamination left on the in-line-diffused emitter surface after PSG removal can significantly compromise contacting and surface passivation. The SERIS etch process simultaneously removes these residual surface contaminants associated with in-line diffusion, along with providing an emitter etch-back. Fig. 3 shows SEM micrographs of the in-line-diffused mono-Si surface after different processing stages [7]. Even after PSG removal, a considerable amount of foreign material is visible on the surface (R_{sq} ≈ 50Ω/sq, see Fig. 3(a)). The white scaling in Fig. 3(a) represents the visible imprints of the surface contamination which will reduce the solar cell efficiency. The SERIS etch, however, effectively removes the foreign material, while maintaining the conformity of the pyramids (Fig. 3(b)). Basically the chemistry of the SERIS etch removes the deposited hard surface 'debris' arising from the in-line diffusion process. As clearly shown in Fig. 3(b), after etch-back there is an absence of surface debris, and just nanometre-size pinholes remaining in the clean Si areas.

Application of the 'SERIS etch' to in-line-diffused emitters

As discussed earlier, the SERIS etch is especially beneficial for in-line-diffused emitters and has already been successfully used to fabricate high-efficiency full-area Al-BSF homogeneous-emitter, selective-emitter (SE) and Al-LBSF Si wafer cells, with respective maximum efficiencies of 18.3% [8], 18.7% [9] and 19.0% [7]. In the case of Al-BSF and Al-LBSF solar cells, the emitter was etched back from an initial R_{sq} value of ~40–50Ω/sq to ~70Ω/sq. For SE cells, by using the SERIS etch, a unique SE process has been developed with fewer processing steps [10] compared with conventional processes [6]. In contrast with a standard in-line-diffused etch-back emitter of R_{sq} ≈ 60Ω/sq, in-line-diffused SERIS SE full-area Al-BSF cells demonstrate an efficiency gain of $0.4\%_{abs}$ [9].

> "An efficiency greater than 19% seems achievable using SE and Al-LBSF-type solar cells."

An 18.6% average cell efficiency was recently reported [11] for full-area Al-BSF homogeneous-emitter cells with an additional optimization of chemical rear-junction isolation, screen parameters and

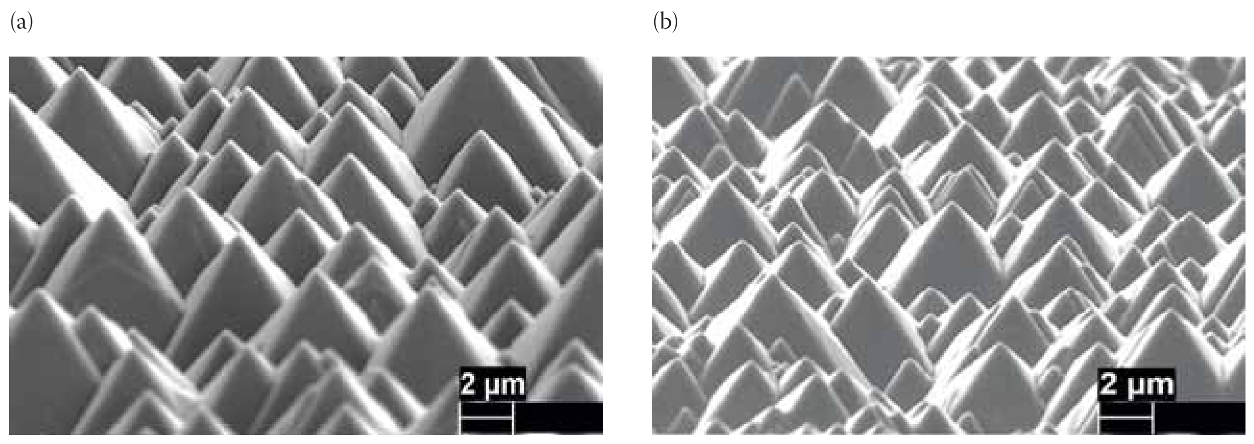

Figure 2. Scanning electron microscope (SEM) micrographs of the pyramid-textured mono-Si surface viewed at an angle of 70° (×5000 magnification): (a) textured surface (undiffused); (b) in-line-diffused surface after etch-back with the SERIS etch (R_{sq} ≈ 100Ω/sq).

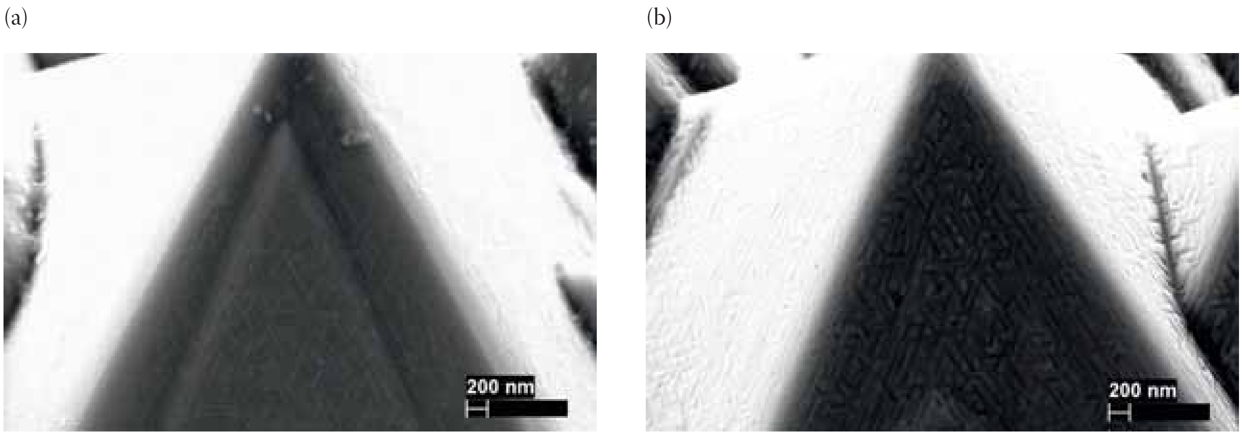

Figure 3. SEM micrographs of the in-line-diffused mono-Si surface viewed from above (×20,000 magnification): (a) after PSG removal of the 50Ω/sq diffused emitter; (b) the same surface after etch-back to R_{sq} ≈ 70Ω/sq with the SERIS etch [8].

Cells	V_{oc} [mV]	J_{sc} [mA/cm^2]	Fill factor [%]	Efficiency [%]
No etch-back	618.5	36.6	75.3	17.0
Etch-back by SERIS etch	629.6	36.7	80.2	18.6
Change (absolute)	+11.1	+0.1	+4.9	+1.6

Table 1. Summary of the average one-sun *I-V* parameters for in-line-diffused emitter mono-Si wafer solar cells without etch-back (as-diffused 70Ω/sq emitter) and with etch-back (as-diffused 40Ω/sq emitter with etch-back to 70Ω/sq).

metal co-firing processes. On the basis of this improved 'baseline' efficiency, an efficiency greater than 19% seems achievable using SE and Al-LBSF-type solar cells. To the authors' knowledge, these are the highest reported efficiencies achieved so far with in-line-diffused emitters using screen-printed contacts, which demonstrates the effectiveness of the SERIS etch.

Average values of the electrical parameters of the completed in-line-diffused solar cells (measured under standard one-Sun AM1.5G conditions) are summarized in Table 1, for both non-etch-back cells (as-diffused emitter with R_{sq} ≈ 70Ω/sq) and etch-back cells using the SERIS etch (as-diffused R_{sq} ≈ 40Ω/sq emitter and then etch-back to ~70Ω/sq). The dominant performance gain when using the SERIS etch is a result of the 11.1mV increase in V_{oc} and the 4.9% gain in fill factor, yielding an average 1.6%$_{abs}$ efficiency gain for the etch-back cells compared with the cells without etch-back.

It is assumed that the presence of sufficient residual surface contaminants obstructs the creation of ohmic contact during metallization. The removal of contaminants by the SERIS etch improves the ohmic contact, ultimately resulting in lower values of series resistance over the entire in-line-diffused emitter surface. Additionally, because of the residual surface contamination and silicon phosphide precipitates [1] with the heavily doped dead layer, cells without etch-back suffer losses in Voc and short-circuit current density (J_{sc}). The SERIS etch eliminates all these negative aspects of in-line diffusion, allowing V_{oc} and J_{sc} values to be obtained that are on a par with those of tube-diffused emitters.

Industrial application of the SERIS etch

To date, the SERIS etch has been applied in a batch process in the laboratory at SERIS. However, the authors are confident that the SERIS etch can be easily transferred to industrial in-line wet-chemistry tools. The SERIS etch process is normally performed at 80°C, and there is no significant evaporation of the chemical components, which would affect the concentration of the solution. Moreover, no hazardous HF and HNO_3 solutions are used. As a result, the SERIS etch is compatible with existing alkaline-texturing tools, which are already designed for processing with ~80°C alkali solutions. The only required modification envisaged is a shortening of the process tool because of the shorter process time (as per requirements) of the SERIS etch than that required in alkaline texturing.

> "The SERIS etch has already demonstrated world-leading solar cell efficiencies for in-line-diffused solar cells."

Conclusion

In this paper it has been shown that the low-cost HF-free non-acidic SERIS etch has unique properties that make it an ideal process for the cost-effective manufacture of high-efficiency Si wafer solar cells. The new etch technique offers uniform, conformal, deep etch-backs that also serve to remove the detrimental debris typically present after in-line diffusion. Since the SERIS etch is compatible with existing in-line industrial tools for alkaline texturing, its transfer to the PV industry is expected to be relatively straightforward. The SERIS etch has already demonstrated world-leading solar cell efficiencies for in-line-diffused solar cells, with efficiencies of up to 18.7% for standard homogeneous-emitter Al-BSF solar cells, and is also compatible with SE and LBSF solar cells.

Acknowledgements

The authors thank their colleagues from the Silicon Photovoltaics Cluster at SERIS for their assistance in sample processing and characterization. SERIS is sponsored by the National University of Singapore (NUS) and Singapore's National Research Foundation (NRF) through the Singapore Economic Development Board (EDB).

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Cell Processing

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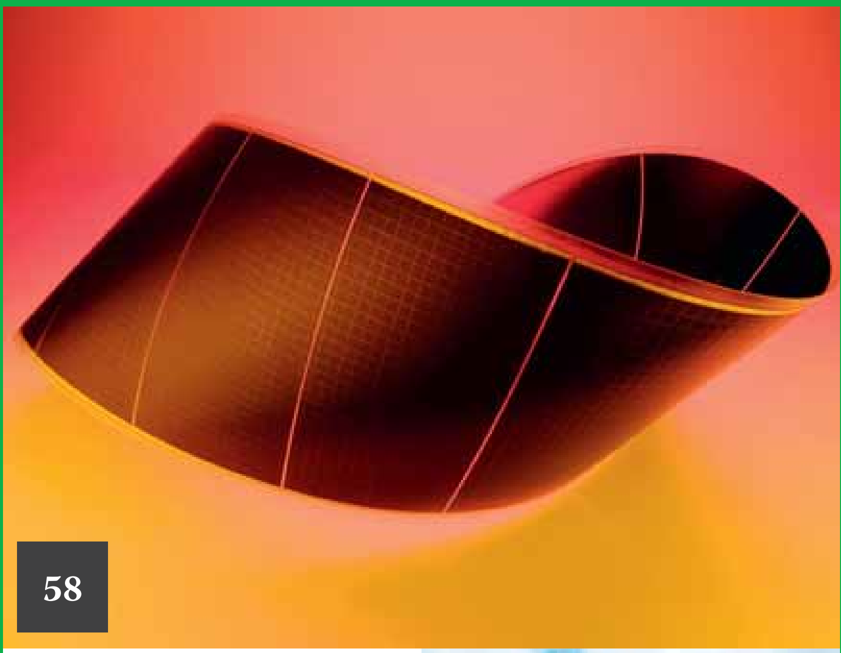
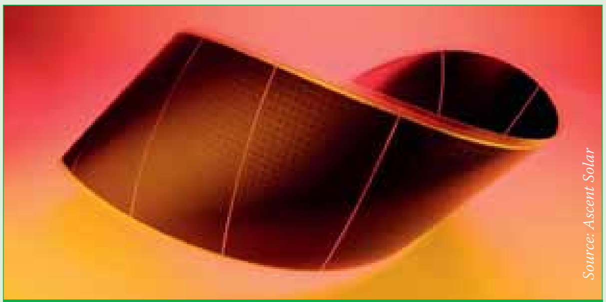
Thin Film



First Solar and Intermolecular prep disruptive new approaches to CdTe thin-film advancements

First Solar and Intermolecular are planning to extend a previous R&D collaboration established last year and develop what they describe as "disruptive new approaches" to boosting the solar cell conversion efficiencies of First Solar's CdTe solar cell technology. According to First Solar, the new two-year partnership programme is expected to target module conversion efficiency gains well beyond its previously announced roadmap, while attempting to shorten the 'time to market' of technology.



"Disruptive new approaches" to boosting the solar cell conversion efficiencies have been developed.

Record Cell Efficiencies News Focus

Source: Solar Frontier

Solar Frontier has broken the record for CIS thin-film solar cell conversion efficiency.

Record breaking: Solar Frontier pushes CIS thin-film efficiency to 19.7%

Solar Frontier has broken the record for CIS thin-film solar cell conversion efficiency using a sputtering and selenization process. The current CIS efficiency record at 20.3% was set with the co-evaporation processes. The record conversion efficiency figure of 18.6%, verified by Japan's Advanced Industrial Science and Technology, had stood for 10 years. However in a joint collaboration with Japan's New Energy and Industrial Technology Development Organization, Solar Frontier has pushed the record to 19.7%, using solar cells measuring approx. 0.5cm^2, cut from a 30x30cm substrate.

TSMC Solar touts new CIGS thin-film module efficiency

CIGS thin-film module manufacturer, TSMC Solar has boosted its champion module efficiencies to 15.1%, a 0.9% increase barely five months after reporting efficiencies of 14.2% in September 2012. The 15.1% module total area efficiency record was produced with its commercial-sized (1.09m^2) substrate at its manufacturing facility in Taichung, Taiwan. Both TÜV SUD and UL testing houses verified the module efficiency levels.

Empa achieves record 20.4% efficiency for flexible thin film

Scientists at Empa, the Swiss Federal Laboratories for Materials Science and Technology, have developed thin film solar cells on flexible polymer foils with a new record efficiency of 20.4% for converting sunlight into electricity. Empa said the cells are based on CIGS semiconducting material (copper indium gallium (di) selenide) known for its potential to provide cost-effective solar electricity. The technology is awaiting scale-up for industrial applications.

Verified: Heliatek organic solar cell achieves record 12% efficiency

Heliatek has achieved a record 12% conversion efficiency in its organic PV (OPV) cells using a vacuum-deposition process. The record has been verified by accredited testing facility SGS and beats Heliatek's previous, hitherto unbroken record of 10.7%. According to the company the record-setting organic solar cell was fabricated using a 1.1cm^2 cell size that combined two patented absorber materials, converting at two different wavelengths. High temperature operation of the OPV cell, coupled with its low light capturing capabilities was said to be comparable to about 14% to 15% efficiency for traditional crystalline silicon and thin film technologies.

Sharp's triple-junction InGaAs solar cell reaches record 37.7% conversion efficiency

A CPV triple-junction compound solar cell developed and optimised by Sharp Corporation has been verified by Japan's National Institute of Advanced Industrial Science and Technology with a record conversion efficiency of 37.7%.

Sharp used an InGaAs (indium gallium arsenide) combination as the bottom absorption layer while increasing the active area at the cell edges. The R&D program was supported by Japan's New Energy and Industrial Technology Development Organization. The device is targeted at CPV applications as well as space satellites and vehicles.

Source: TSMC Solar

TSMC Solar has boosted its champion module efficiencies to 15.1%.

R & D News Focus

South Korea and Morocco cooperate on thin-film solar research

The Korea International Cooperation Agency and Morocco's Research Institute of Solar Energy and New Energy (IRESEN) have announced a collaboration on thin-film research. Managed by Morocco's Ministry of Energy Mines, Water and Environment, Korea will send academics to Morocco to train researchers and engineers in order to complete IRESEN's goal of setting up a national research, development and innovation laboratory for thin-film technology. The research centre will be located in Benguerir, north of Marrakesh, next to the Mohammed VI Polytechnic University.

Swiss Federal Institute of Technology achieves record conversion efficiency

The Swiss Federal Institute of Technology yesterday announced it has achieved a conversion efficiency of 10.7% for a single-junction microcrystalline silicon thin-film solar cell. The new record for this type of cell has been confirmed by the independent institute, Fraunhofer Institute for Solar Energy Systems (ISE). According to the Swiss Federal Institute of Technology in Lausanne, the record cell efficiency was achieved using 1.8 micrometers of thin silicon active material, which is 100 times less material than is used for conventional PV technologies. The Swiss Federal Institute of Technology claims that this type of thin-film silicon technology could eventually lead to module production prices as low as €35 (US$47) per square metre.

Solliance OPV R&D alliance gets ThyssenKrupp to join for BIPV applications

ThyssenKrupp Steel Europe has joined the Solliance (ECN, imec, TNO, Holst Centre, TU/e, Forschungszentrum Jülich) R&D alliance that is focused on organic photovoltaics (OPV) thin film technologies. ThyssenKrupp is following the likes of Tata Steel and partner Dysol in tapping thin film OPV for BIPV markets, where large-area steel flat roofing is combined at the production step for solar applications. Solliance was established just over a year ago to promote thin-film PV development in the Eindhoven-Leuven-Aachen region.

Business News Focus

XsunX prepares for trials of new CIGS system

California-based XsunX has completed the assembly of its new CIGS (copper indium gallium selenide) thin-film cell manufacturing system. The company now hopes to begin customer demonstrations of the CIGSolar system, with which it said it had achieved cells of 15.91% average efficiency in National Renewable Energy Laboratory tests.

Solar Frontier posts first positive quarterly results; sales hit US$833 million in 2012

Solar Frontier strengthened its position as the closest thin-film PV module manufacturer competitor to First Solar in 2012, posting record revenue of ¥78.2 billion (US$833 million). The Japanese CIS thin-film technology leader reported an 18.9% increase in sales for the full year. The company reduced its operating loss to ¥15.4 billion in 2012, a ¥13.4 billion reduction from the previous year. Solar Frontier posted an operating income of ¥15.4 billion in 2012, up by ¥13.4 billion compared to the previous year. Significantly, the company reported a small operating income of ¥0.1 billion for the fourth quarter of 2012, the first time the company has reported positive quarterly operating income since starting manufacturing operations in 2010. The company also highlighted its success in overseas markets as Solar Frontier's CIS thin-film modules were used on PV projects by NRG Solar LLC and EDF Renewable Energy, formerly enXco in the US. Solar Frontier is said to be producing in volume CIS modules with 13% conversion efficiencies.

PVcomB selects Smit Ovens CIGS selenization system for R&D

As part of its technology roadmap to boost high-efficiency CIGS cells, the Competence Centre Thin-Film- and Nanotechnology for Photovoltaics Berlin, PVcomB, has ordered an active selenization system from Smit Ovens BV. The newly developed active selenization system is said to be specifically designed for flexible R&D workloads and is capable of running 300x300mm substrates. The system's active reactor design is said to offer a high level of thermal stability, typically needed in a reliable mass production environment.

Flisom raises funding to ramp up 15MW flexible CIGS production plant

Flisom, a Swiss company which develops technologies for manufacturing flexible thin film CIGS solar modules (copper indium gallium (di)selenide), reports that it has raised an unspecified but "substantially large" investment to further develop its technology and build a production plant with an annual capacity of 15MW in Switzerland. Besides securing financial backing, Flisom also signed an agreement with Empa, the Swiss Federal Laboratories for Materials Science and Technology, to provide research and development support

© Flisom AG

Flexible solar module based on CIGS thin-film technology manufactured by Flisom, Switzerland."

on high-efficiency flexible CIGS solar cell technology. Flisom's third funding round was completed with participation of a Swiss investor along with Flisom's existing strategic investor, Indian multinational conglomerate, Tata Group.

Thin-film start-up G24 Innovations enters administration

UK-based dye sensitised solar cell (DSSC) flexible thin-film manufacturer, G24 Innovations has sought protection under administration, according to reports.

The flexible thin-film firm is based in Cardiff, Wales, and employs 40 people. Administrators are hoping to save the business as a going concern, though did not say whether this would be achievable or whether a buyer would be sought. A relative latecomer to the market, G24 Innovations attempted to position the company in providing bespoke products for niche markets, primarily in the indoor/outdoor consumer sector as well as low-level charging and lighting markets for off-grid applications for the poor or low-income markets in developing countries.

Canadian Solar and Strata Solar to build 15 utility-scale PV projects in North Carolina

A total of 15 PV projects equal to approximately 85MW are to be built by project developer, Strata Solar and module manufacturer Canadian Solar in 2013.

The first project to be commissioned is Fuquay Farm, a 6.4MW (DC) project located in Middle Creek, Willow Springs in Wake County, NC. According to the companies, the project broke ground in November 2012 and will be commissioned by the end of February. The rest of the projects are said to include mainly 6MW sized utility-scale projects, but will also include a 1MW rooftop solar system and a 3MW solar farm. All 15 projects are expected to be completed in 2013.

First Solar chart-topping prevents talk about a revolution

First Solar is forecast to have been the largest midstream solar PV cell manufacturer in 2012, according to recent checks and preliminary estimates by NPD Solarbuzz of internal (in-house) cell/midstream PV production levels during the calendar year 2012.

Once again, First Solar is believed to have produced more midstream-MWdc of product than any other c-Si cell or thin-film producer in the world. And at a time when many in the industry are seeking to combat a perceived China-led PV manufacturing revolution, this humbling statistic provides a different slant on how participating in the PV industry is not just about taking on competitors on a legacy like-for-like/capacity-counting basis.

Source: First Solar

First Solar has released its new Series 3 FS-392 thin-film module, which has a 92.5W rating.

InnoLas Systems shows 60% revenue growth in 2012

Germany-based industrial laser specialist InnoLas Systems GmbH said that the company achieved revenue of €40 million (US$52.9 million) in 2012, which was 60% higher than the previous year. Despite the lack of orders from the PV industry for the vast majority of equipment suppliers, InnoLas Systems said that more than 90% of revenue growth in 2012 was actually generated from sales in the PV industry, bucking the trend.

First Solar releases new Series 3 thin-film module

Thin-film manufacturer First Solar has released its new Series 3 FS-392 thin-film module, which has a 92.5W rating. The FS-392 module conforms to all current IEC certifications and UL listings for the Series 3 family, including the UL listing for 1000V systems. Tom Kuster, First Solar vice president of product management and system technology said: "This increase in module efficiency, coupled with our thin-film technology's real-world yield advantage when compared to crystalline silicon PV, results in higher energy density and lower levelized cost of energy."

Tokyo Electron disbands thin film JV with Sharp

A small JV company, established between Tokyo Electron (TEL) and Sharp Corporation in 2008 to develop plasma CVD systems for use in thin-film silicon solar photovoltaic cells has been dissolved by TEL. TEL said that the JV, Tokyo Electron PV had planned to operate for five years, yet a review of future activities in the field led to the decision to disband the business a year early. However, the company did not say directly that this was due to the recently finalized acquisition of Oerlikon Solar, which had competing technology as well as offered turnkey silicon thin-film manufacturing lines.

Product Reviews

Advanced Energy

Advanced Energy provides improved plasma management

Product Outline: Advanced Energy Industries has introduced its 'Paramount 2 MHz' power system, designed to span frequencies from 400kHz to 60MHz, providing plasma management in complex thin-film processing environments.

Problem: The Paramount RF pulsing provides improved synchronized, multi-frequency RF power to improve etch rate selectivity, substrate profile control and film uniformity in a wide operating window.

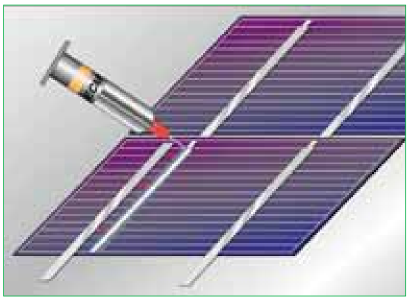
Solution: The common controls, measurement and advanced features facilitate process integration and optimization across multiple frequencies without the need for customization or complicated protocols. In addition, the Paramount's advanced pulsing technology, combined with AE's Navigator II matching network's tune-while-pulsing capability, delivers improved plasma control. Its built-in ability to synchronize with other Paramount units simplifies power supply integration and operation across multiple frequencies, while its advanced pulsing features – such as user-selectable pulse and phase synchronization and sophisticated arc management – provide precise RF.

Applications: Development of advanced materials and new device geometries in thin-film processing applications.

Platform: AE's Paramount RF power-delivery platform, including the new Paramount MF product, works with its Navigator II digital matching network, incorporating tune-while-pulsing capability for highly stable plasma and smooth power delivery, and Sekidenko optical fibre thermometers, delivering high-speed, multi-channel wafer temperature monitoring and control among other features.

Availability: January 2013 onwards.

Engineered Conductive Materials



ECM offers low-temperature curing conductive adhesive

Product Outline: Engineered Conductive Materials is offering the 'DB-1569-1' low-temperature curing conductive adhesive for use in organic photovoltaics (OPV). This material formulation has been optimized for improved conductivity and stability on various substrates when cured at 80°C or higher.

Problem: OPV laminates require low-temperature processing to prevent damage. Conductive adhesives that provide correct stability for life-cycle requirements and the often-flexible applications used in OPV are essential.

Solution: DB-1569-1 is more than 90% cured after 30 minutes at 80°C, with a dispensing work life greater than 48 hours (measured as a 25% increase in viscosity), while maintaining optimized rheology for dispensing and excellent damp heat resistance and conductivity stability on tin, tin-silver and silver-plated ribbons. DB-1569-1 features extreme flexibility that is ideal for flexible applications with high peel strength to withstand the stresses induced in flexible BIPV and display applications.

Applications: Low-temperature OPV thin-film laminates.

Platform: This material can also be fast cured at elevated temperatures (1 minute at 180°C).

Availability: January 2013 onwards.

SURAGUS GmbH

'EddyCus Thin-Film' lab designed for contact-less real-time thickness

Product Outline: SURAGUS GmbH, a spin-off from the Fraunhofer Institute for Non-Destructive Testing in Dresden, offers the 'EddyCus Thin-Film' lab specifically for contact-less real-time thickness and sheet resistance determination of low- and high-conductive thin-films on glass, wafer, plastics or foils.

Problem: Functional thin films on float glass and foils are used in photovoltaic cells, touch screens, flat panel displays, OLED lighting and smart glass applications or anti-static films or surface heating applications. Quality assurance and process monitoring is required in order to ensure an optimal and homogeneous conductive functionality of thin films.

Solution: The EddyCus Thin-Film lab employs the eddy current method that utilizes local conductivity variations of the test objects for the characterization of correlated quality characteristics, such as thickness, conductivity, homogeneity and purity or physical changes. The complex eddy current signal contains various data about the test object, which can be separated into simple or complex algorithms. The eddy current testing technology is based on a powerful eddy current electronics with a frequency range from 10kHz to 100MHz, which is combined with different sensor concepts depending on the application.

Applications: Contact-less conductivity measurement of functional thin films (e.g. TCOs).

Platform: The system is connected to a measurement PC via ethernet. Sheet resistance range: 0.01-1Ohm/sq; 1-100Ohm/sq; substrate supporting surfaces of 100x100mm^2, 200x200mm^2 and 300x300mm^2 available. Measurement of gaps 1, 5, 15, 25, 40 and 60mm is available (special sizes on request).

Availability: Currently available.

Current topics in CIGS solar cell R&D – Part 2: Buffer layers and metastabilities in CIGS

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ABSTRACT

This is the second part of a review article series about current topics in R&D concerning Cu(In,Ga)$(Se,S)_2$ – or CIGS – solar cells. In the first part, which appeared in the previous edition of *Photovoltaics International*, the focus was on CIGS absorber layer formation. This second part will discuss another essential part of CIGS solar cells – the buffer layer – in conjunction with metastabilities in these types of cell.

Introduction

Cadmium sulphide (CdS) deposited by chemical bath deposition (CBD) is commonly used as a buffer layer, but more and more emphasis is now being placed on alternative Cd-free materials and new dry techniques. However, metastabilities – which relate to changes in Cu(In,Ga)$(Se,S)_2$ (CIGS) solar cell performance due to light, thermal or voltage bias treatments – often occur with Cd-free buffer layers. In contrast to light-induced degradation (LID) in a-Si based solar cells [1], or thermal-induced degradation in CdTe-based cells [2] because of Cu diffusion, these metastabilities have mostly a beneficial effect on solar cell efficiency. There have been several empirical investigations [3] of these metastable effects in CIGS solar cells, showing the different changes in solar cell behaviour depending on the actual treatment of the device. All these observations can be explained by the $(V_{Cu} - V_{Se})$ divacancy complex [4], which leads to changes in the net doping in the CIGS absorber layer.

"Metastabilities often occur with Cd-free buffer layers."

Buffer layer – the secret to creating good CIGS solar cells

In comparison with common crystalline silicon-based solar cells, CIGS solar cells have a so-called heterojunction, which creates the electric field necessary for charge separation. In the case of CIGS solar cells the heterojunction is accompanied by three features:

- The CIGS absorber layer, which is a p-type semiconductor and is the light-absorbing and current-generating part of the solar cell.
- A transparent conducting oxide (TCO) window layer, which serves as the front contact and – since the TCO layer consists of an undoped ZnO and highly doped degenerated ZnO – is part of the p-n junction.
- A buffer layer, commonly made of CdS, between the absorber and window layers. The buffer layer fulfils several different roles and will be discussed in this paper.

Drawing the band diagram of the hetero-structure offers further insights into its structure (Fig. 1). In the case of a CIGS solar cell, at least three different materials with different band gaps and doping levels are involved. First, there is the window layer consisting of a bi-layer of Al-doped ZnO (AZO) and undoped ZnO (i-ZnO); both layers have a band gap of about 3.4eV and are transparent with respect to the visible and near-infrared light. The Fermi level lies just above the conduction band for the AZO layer and just below it for the i-ZnO layer. Next is the buffer layer: in the case of CdS, this layer is slightly n-doped and has a band gap of 2.4eV. This is followed by the p-type CIGS layer with a band gap of between 1.0eV and 1.3eV for most commercial devices.

As the energy of the Fermi level has to be the same in all layers this would lead to a stepwise increase either in the conduction band or in the valance at the interfaces between the layers. Band bending therefore occurs, which smooths out these barriers to achieve band alignment if possible. As can be seen in Fig. 1(b), between the chalcopyrite layer and the CdS layer, an electron barrier in the conduction occurs (a so-called 'spike'). At this barrier, electrons are blocked and the device current collection is degraded. Numerical simulations show that, for CIGS solar cells, a small spike is beneficial, as it leads to an

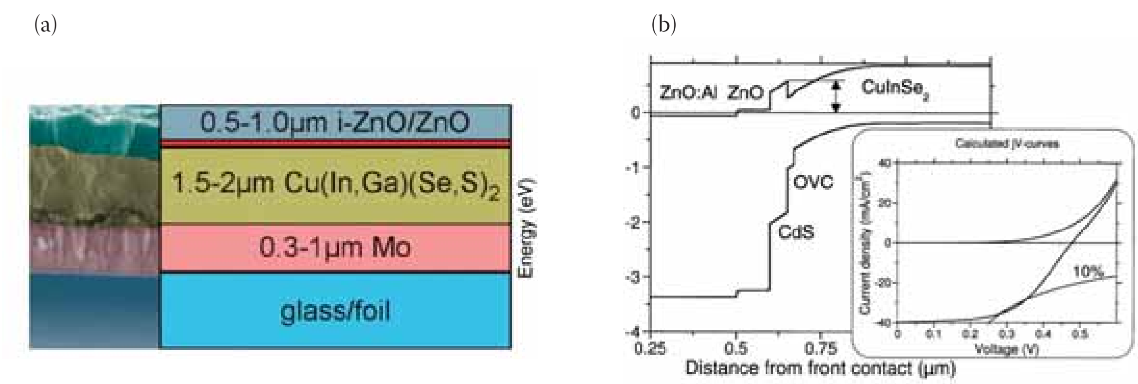

Figure 1. (a) Schematic of a CIGS solar cell (SEM cross-section on left). (b) Band diagram and simulated *I-V* curve (after Klenk [5]).

Buffer material	Band gap	Technology	Commercial application
CdS wet	2.4eV	CBD	Bosch, Würth, Solibro
CdS dry	2.4eV	Sputter	Miasole, Midsummer
Zn(O,S) dry	3.3–3.6eV Depends on S, with a minimum of 2.6eV at S/(S+O)=0.7	Sputter, ALD	–
Zn(O,OH,S) wet	3.7eV Mixture of ZnO, ZnS and $Zn(OH_2)$	CBD	Solar Frontier
In_2S_3 dry	2.0–2.8eV	Evaporation, ALD	Avancis (Evaporation)
In_2S_3 wet	2.0–2.8eV	CBD, ILGAR, Spray Pyro	Honda (CBD)

Table 1. Band gaps, deposition technologies and commercial applications for different buffer materials.

interface inversion, or in other words n-type behaviour at the absorber–buffer interface.

On the other hand, if the conduction band drops at the interface (a so-called 'cliff'), enhanced interface recombination will occur, which will cause a decrease in the open-circuit voltage of the device. If the conduction band arrangement cannot be modified, the band gap close to the interface should be widened by lowering the valence. This can be achieved by adding gallium or sulphur to the top region of the absorber layer or by creating a CIGS top layer that is very low in copper.

As already mentioned, CdS as the buffer layer works very well in CIGS solar cells, even if its band gap is not optimal because current in the blue part of the spectrum is lost. The use of CdS has a historical basis, as the original development of CIGS solar cells began with CuS/CdS devices; moreover, CdS works well in CdTe-based solar cells.

In most cases, CdS is deposited by chemical bath deposition using Cd acetate ($Cd(OH)_2$) and thiourea (CH_4N_2S) as precursors in an ammoniac (NH_3) solution. The treatment of the CIGS absorber layer in the bath has its own advantage, as the absorber surface is cleaned again. As mentioned before, the band alignment between the CdS and the CIGS layers depends on the actual band structure at the absorber surface, and this alignment might lead to metastabilities, which will be discussed later. As the CdS deposition is the only wet-chemical process in a typical CIGS production line, a lot of research has been carried out on dry deposition methods, such as evaporation, sputtering and atomic layer deposition (ALD). Alternative Cd-free materials have also been investigated, to avoid the use of Cd and to increase the band gap of the buffer layer.

Nevertheless, CdS is the workhorse in almost all R&D CIGS-based production lines, because the deposition procedure is easy to perform and results in the best efficiencies. All record-breaking devices use CdS as the buffer layer – the reason why this is true, however, is still not known. The following possible explanations are under discussion:

- Optimal band alignment, even if there is a small spike
- Protection against sputter damage
- Cleaning of the absorber surface; removal of the secondary phase at the surface
- Best lattice matching between CIGS and ZnO
- Correct size of Cd atom to fit in a Cu-poor CIGS surface that is acting as an n-type dopant (shallow donor)

Cd-free buffer layer and alternative deposition methods

There are two reasons why the development of alternative buffer layers and deposition methods is important. First, a Cd-free buffer layer would create a more environmentally friendly product. This is required in Japan: two Japanese companies having CIGS module production facilities – Solar Frontier and Honda Soltec – both implement Cd-free buffer layers. Second, and more importantly, superior band gap materials would lead to greater current generation and better efficiencies.

In a review article, Naghavi et al. [6] summarized the efforts that have been made within the last few years regarding Cd-free buffer layers. Table 1 gives an overview of the materials that were used as buffer layers, and the corresponding band gaps and deposition technologies. Only two Cd-free buffer layers were found to be comparable to CdS: Zn(O,S) and In_2S_3. In the case of Zn(O,S), the band gap depends on the S/(S+O) ratio, ranging from 3.3eV for pure ZnO to 3.6eV for pure ZnS, with a minimum of 2.6eV at a S/(S+O) ratio of 0.7. For the band gap with an In_2S_3 buffer material, however, several values between 2.0eV and 2.8eV were reported, but it is not clear whether In_2S_3 is a direct or an indirect semiconductor.

"A Cd-free buffer layer would create a more environmentally friendly product."

Alternative techniques to CBD are under investigation because a wet-chemical deposition step interrupts an otherwise dry processing step during CIGS module production. In particular, direct evaporation and sputtering are promising methods for reducing the cost of deposition of the buffer layer. Two interesting alternatives are spray ILGAR – ion layer gas reaction – and ALD, since both of these methods allow a very conformal growth of the buffer layer.

Spray ILGAR was developed at the Helmholtz-Zentrum Berlin [7] and

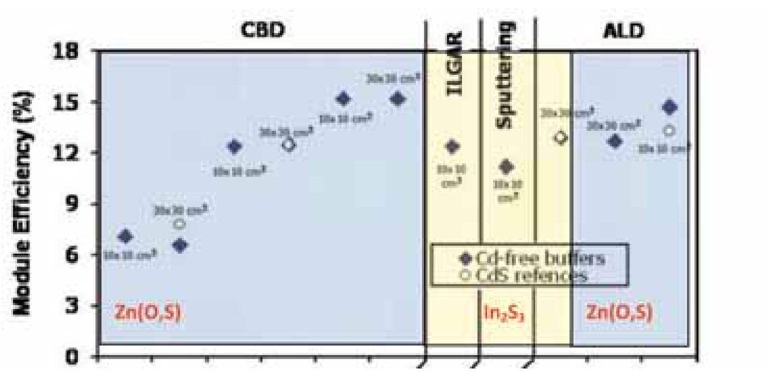

Figure 2. Best chalcopyrite solar cells and mini-modules with Cd-free buffer layers prepared using different technologies (after Naghavi et al. [6]).

involves the generation of an $InCl_3$/alcohol aerosol, which is transported in a N_2 stream to the hot substrate (200–250°C); by using a chemical vapour deposition process, an In(Cl,O,OH) precursor layer is formed and subsequently converted into In_2S_3 in a H_2S atmosphere. The chlorine in the process seems to have an active role and has to be adapted to every absorber layer.

ALD of Zn(O,S) allows conformal growth of the buffer layer, avoiding pinholes. The scalability of the ALD process is currently being investigated at PVcomB, using a batch reactor system for up to seven 30 × 30cm^2 substrates.

Both of these alternative technologies have the disadvantage that they cannot be integrated into other deposition tools in a CIGS production line. However, efficiencies similar to those of solar cells undergoing CBD CdS have been demonstrated (Fig. 2).

From a production perspective, techniques such as sputtering or evaporation of the buffer layer material are much more interesting. Avancis announced that they have developed a buffer layer process using evaporated In_2S_3. This process could be integrated into the CIGS-formation equipment using the heat of the evaporation process or thermal annealing process, whereas sputtering could be combined with the window layer deposition.

Most alternative buffer layer technologies require higher deposition temperatures or more post-annealing steps. In the case of CBD Zn(O,S), up to 30 minutes' annealing at 200°C and light soaking are required to produce high-efficiency solar cells [8]. In_2S_3 buffer layers are generally deposited at a temperature of around 200°C. Whether this high temperature is necessary to form a 'better' buffer layer or to cause some interdiffusion between the absorber and buffer layers is not fully understood. In the case of In_2S_3, however, interdiffusion has been observed [9]. Nevertheless, solar cell devices employing alternative buffer layers are more sensitive to metastable behaviour, which will be discussed next.

"Solar cell devices employing alternative buffer layers are more sensitive to metastable behaviour."

Metastabilities in CIGS solar cells

Transient or metastable effects in CIGS-based solar cells have been reported since the beginning of their development. After preparation, the CIGS-based solar cell in a relaxed state has a very low net acceptor doping density of less than $10^{-15}cm^{-3}$, leading to a reduced open-circuit voltage (V_{oc}) and fill factor (*FF*), a kink in the *I-V* curve, a reduced short-circuit current density (J_{sc}), or a crossover of dark and light in the *I-V* curve around V_{oc}. Table 2 summarizes the observed changes in a CIGS-based device which was stressed under different conditions.

A device will generally see increased performance after illumination and forward bias, which is the case in normal solar cell operation. This increase is caused by a change in the net acceptor concentration. However, special care has to be taken during development because of the following:

1. The CIGS solar cell after processing might not be in a relaxed state or at the maximum net acceptor density.

2. Storage in a dark environment will lead to changes, especially since some of the effects have time constants of several days.

3. Measuring a device will change it. Extra care has to be taken especially if the device is put under reverse bias. A hysteresis effect may be observed if the *I-V* curve measurements are taken from reverse to forward bias and back. Before taking measurements for *I-V* curves, the following rules should therefore be considered:
   a. Define a pretreatment of the CIGS-based solar cells, including light soaking and/or thermal annealing.
   b. Always measure in the same direction, preferably from forward to reverse bias.
   c. Do not stress the cell too long under reverse bias, and do not apply too high a reverse-bias voltage.

4. Alternative buffer layers are more sensitive to metastable changes.

5. Dark *I-V* curves should always be inspected, as not all optimal devices will exhibit voltage-dependent current collection (extreme cases show crossover).

Often devices from the early beginnings of ramping-up CIGS solar cell production lines, in either research or industry, show more pronounced light-soaking effects than devices from established laboratories. Additionally, CIGS cells with Cd-free buffer layers are more sensitive to experiencing changes. The theoretical background of the underlying effect and its consequences will be discussed in the next section.

Theoretical explanation of metastabilities in CIGS and how to avoid them

All observed changes can be explained by a change in the net acceptor concentration.

Solar cell bias	Observed change	Derived change	Comment	Relaxed condition
Red light, r.t.	V_{oc}+, C+, σ+, N_d+	Persistent photoconductivity Increase in net acceptor density	Same as forward bias	Dark, annealing at 340–360K
Blue light, V_{oc} r.t.	*FF*+	Change in buffer layer	Reduction of barrier between buffer layer and CIGS	Dark, annealing at 340–360K
White light, V_{oc}	V_{oc}+, *FF*+, C+, σ+	Persistent photoconductivity Increase in net acceptor density Change in buffer layer (Cd-free)	No barrier in buffer layer	Dark, annealing at 340–360K
Forward bias, dark, r.t.	V_{oc}+, C+, σ+, N_d+	Increase in net acceptor density Creation of hole trap E_d = 0.26eV	Same as red light bias	Dark, annealing at 340–360K
Reverse bias, dark, r.t., -1V, 1h	C+, *FF*-	Increase in net acceptor density	Can be accumulated; drastically reduces efficiency	Dark, annealing at 340–360K

Table 2. Observed metastable change in a CIGS solar cell for different bias conditions at room temperature (r.t.). (C = capacitance, σ = conductivity, E_d = deep-defect energy, N_d = doping density.)

Lany and Zunger [4] therefore proposed a ($V_{Se} - V_{Cu}$) divacancy complex (VV), whose charging state depends on the locations of the Fermi level having the characteristics of a relaxed donor model. The main results can be summarized as follows:

1. Donor configuration VV^+ and deep defect VV^0: the In–In bond and defect level are close to the conduction band minimum (CBM).

2. Acceptor configuration VV^-: the In–In bond is broken, the distance is large between the In atoms, and the defect level moves close to the valence band maximum (VBM).

3. The reaction involves the rearrangement of bonds and the change of a shallow donor to a shallow acceptor:
   $$VV^+ + 2e \rightarrow VV^- \quad (A1)$$
   or, $$VV^+ \rightarrow VV^- + 2h \quad (A2)$$

4. The reverse reaction involves the capture of two holes, together with a lattice relaxation:
   $$VV^- + 2h \rightarrow VV^+ \quad (D1)$$

5. The energy barrier in CIGS is approximately 0.1eV for reaction A1 and approximately 0.7eV for reaction A2, while the reverse reaction has a barrier of around 0.3eV.

6. The distribution of the two states of the VV complex depends on the Fermi level. In a solar cell device, the acceptor configuration VV^- prevails.

7. The VV complex introduces a shallow acceptor state and an anti-bonding level of 0.85eV above the VBM, which might trap two electrons at that level if the Fermi level is close enough to the conduction band.

Reaction A1 explains the light-soaking and forward-bias effects (capture of electrons), whereas reaction A2 explains the reverse-bias effect (hole emission) – both of which are metastable states. Reaction D1 describes the relaxation into the stable state over a high barrier, which can be enhanced by temperature [3].

In terms of device properties, it can be concluded that white-light illumination provides extra holes close to the interface, creating a beneficial p^+ layer by increasing the number of VV complexes in the donor state. Unfortunately, these complexes have detrimental effects in both charging states, so processes which lead to a reduced number of such VV complexes should therefore be used. This can be achieved by growing CIGS layers in a multi-stage approach that includes a copper-rich stage to reduce the number of Cu vacancy defects.

"White-light illumination provides extra holes close to the interface, creating a beneficial p^+ layer by increasing the number of VV complexes in the donor state."

Conclusion

Resulting in similar efficiencies and lower production costs, Cd-free buffer layers created by dry deposition methods – such as evaporation, sputtering and atomic layer deposition – are viable alternatives to CdS buffer layers. Moreover, they may even lead to higher CIGS module efficiencies, since less light is lost in the buffer layer. Metastabilities are intrinsic to CIGS-based solar cells and caused by a defect complex of Se and Cu vacancies. Light soaking of CIGS-based devices will improve efficiency, while reverse bias or dark annealing at 80°C will return the devices to a stable, low-performing state. Nevertheless, high-efficiency solar cell devices show less improvement during light soaking, as the number of vacancies is reduced by choosing the 'right' preparation recipe consisting of a Cu-rich phase during CIGS formation.

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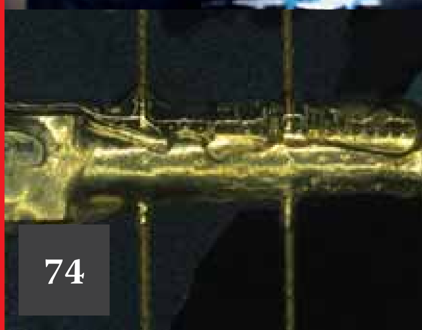
PV Modules



REC modules undergo enhanced testing at SERIS

The Solar Energy Research Institute of Singapore (SERIS) has certified Renewable Energy Corporation's (REC) modules for potential-induced degradation (PID) resistance. SERIS tested REC modules at higher temperatures and relative humidity levels than previously tested and certified at TÜV Rheinland. REC said that under the enhanced PID testing regime at SERIS, the modules experienced less than 2% power degradation. SERIS used negative voltage of 1,000 volts then exposed the modules to an ambient temperature of 60ºC with a relative humidity of 85%, tested for 96 hours. At TÜV Rheinland, modules were exposed to a negative voltage of 1,000 volts in 25ºC temperatures for a period of 168 hours. REC told PV-Tech that the modules certified by SERIS were now in production and would be initially supplied to the APAC and US regions.


Source: REC

SERIS has certified REC modules for PID resistance.

PID Testing & Certification News Focus

Yingli Green's modules pass TÜV SUD's PID testing

Multicrystalline PV modules from Yingli Green have been tested by TÜV SUD for Potential Induced Degradation (PID). According to Yingli Green, power degradation was lower than 0.5%, compared to the maximum allowable power output degradation rate of 5%. TÜV SUD tested modules for 96 hours at 85ºC and 85% relative humidity using the standard 1,000 volts of system voltage bias.

Late last year, US-based independent PV module testing laboratory PV Evolution Labs (PVEL) also carried out PID tests on modules from Yingli Green but over an extended duration of 600 hours.

Panasonic HIT solar modules PID tested by Fraunhofer

Panasonic's high-performance (HIT) PV modules have shown no sign of being affected by potential induced degradation (PID) characteristics after testing took place at the Fraunhofer Center for Silicon-Photovoltaics (CSP). A special PID testing regime was developed by the Fraunhofer CSP to account for Panasonic's unique HIT solar modules. The test developed included both negative and positive voltages, whereby five modules were subjected to +1,000 volts for 48 hours at a temperature of 50ºC with 50% relative humidity and five modules at -1,000 volts over 48 hours. According to the company, no evidence of PID was observed. The Panasonic HIT photovoltaic modules exhibited no sign of degradation under such conditions.

Five tier 1 module manufacturers pass PID testing by PV Evolution Labs

US-based independent PV module testing laboratory, PV Evolution Labs (PVEL) has carried out Potential Induced Degradation (PID) testing programs on modules from Yingli Green, SolarWorld, JA Solar, Kyocera, and Trina Solar. PVEL tested modules at 85˚C at 85% relative humidity for 600 hours that resulted in all manufacturers passing the test. However, the testing house did not provide details on possible PID degradation or which modules from the manufacturers were actually tested. Although no industry-wide acknowledged test standard for PID currently exists, the IEC 62804 standard includes test conditions of 60ºC, 85% relative humidity and a negative 1,000 volts DC charge for a continuous period of 96 hours. However, modules are considered to have passed the test if they show less than a 5% loss in performance of their nominal power.

Source: SolarWorld

Modules are considered to have passed the test if they show less than a 5% loss in performance of their nominal power.

Trina Solar modules receive certifications from PVEL, TÜV Nord

Trina Solar's PV modules have passed testing and been certified for salt mist, sand blast and for reaching PID requirements by TÜV Nord, PVEL and SGS.

TÜV Nord certified Trina's modules as achieving the latest IEC 61701:2011 Severity 1 standards for salt mist corrosion. According to testing conducted by TÜV Nord, Trina's solar modules performed well in ground continuity, wet leakage and insulation resistance. SGS tested the panels in a blowing sand test conducted under DIN EN 60086-2-68 LC2 standards. The results showed little internal impact,

Source: Trina Solar

Trina Solar's PV modules have passed testing by TUV Nord, PVEL and SGS.

certifying Trina Solar modules as being able to perform well in areas with severe sandstorms and/or strong winds.

Testing & Certification News Focus

DelSolar claims to be first Taiwan producer to gain 1000V UL certification

Taiwan-based module manufacturer, DelSolar has received 1000 volt UL certification for a range of its modules. DelSolar claims to be the first Taiwanese producer to receive this certification and that its 60-cell and 72-cell modules, including the D6C_B3A-WS, D6S_B3A-WSf, D6C_B4A-WS and D6S_B4A-WSf series have all qualified.

First quasi-mono-based module tops Photon's field-testing rankings

A 245W quasi-monocrystalline Virtus I module from ReneSola has become the first of its type to top the performance field-testing by Photon Laboratory, a subsidiary of Photon's publishing operations, currently in receivership. This is believed to be the first time that a Virtus product has surpassed monocrystaline-based modules in real world performance tests.

Suntech solar modules shine in desert simulation test

US manfuacturer Suntech's solar modules have passed the 'blowing sand test' by inspection and certification company SGS. This confirms they are suitable for solar installations in desert regions. To determine the effects on solar panels of dust and sand suspended in air, SGS's Desert Dust Test simulates the erosion effects of high-velocity sand particles within dust chambers. Pulses of compressed air are blown through a manifold located in the bottom of a collection trough, forcing dust up and over the solar module. Suntech solar modules passed the maximum power determination, the insulation test and the wet leakage test.

ET Solar modules receive 1000V DC UL certification for US market

Designed for the US market, ET Solar has received 1000 volt DC UL certification by the US-based Electrical Testing Laboratories. The new certification relates to ET Solar's 60-cell and 72-cell polycrystalline modules, which can be used in PV projects employing system voltages up to 1000 volts DC rather than 600 volts DC that are claimed to lower installation costs and improve overall system performance.

MPrime's M200-245P series modules gain Italian fire resistance certification

MPrime, a subsidiary of Martifer Solar has received Italian UNI 9177 Fire Reaction certification, which was carried out by the LAPI laboratory.

Pedro Alves, Managing Director of MPrime said, "This result confirms the high quality of MPrime's products and, most importantly, puts MPrime amongst the few PV producers with UNI 9177 certification, which will allow us to offer added value to our customers, especially in the Italian market."

The company said that its M200-245P series modules a Class 2 rating for fire reaction.

ReneSola modules achieve high scores on newest industry sun simulator

ReneSola announced that its 60- and 72-cell polysilicon and monosilicon solar modules exceeded the company's power output guidelines when assessed by a recent third-party flash test. Four ReneSola modules were tested, all of which produced a maximum power output greater than that indicated on the company's datasheets, by as much as eight watts. The test results confirmed that ReneSola's modules perform at least as well as the

Source: ReneSola

ReneSola modules exceeded the company's power output guidelines.

nominal power outputs and efficiencies stated on the company's datasheets.

Business News Focus

JA Solar raises shipment guidance

JA Solar has raised its shipment guidance for the fourth quarter and full-year 2012. The company said that it expected fourth quarter shipments to be in the range of 480MW to 500MW, significantly exceeding its previous guidance of shipments being between 380MW and 420MW.

As a result, full-year 2012 shipments are expected to be in the range of 1.68GW to 1.70GW, compared to past guidance of 1.55GW to 1.65GW. Shipments include solar wafers and solar modules. JA Solar is expected to release fourth quarter and full-year results on March 18, 2013.

Yingli Green becomes largest solar company; exceeds 2012 module shipment guidance of 2.2GW

Yingli Green has surpassed Suntech Power Holdings as the largest PV company in the world, based on revised full-year module shipment guidance. In advance of its fourth quarter 2012 financial results, Yingli Green said that better than expected module shipments in the quarter had resulted in full-year shipments exceeding its 2.2GW guidance. Strong demand in the fourth quarter meant module shipments reached a new historical high, although the company does not provide quarterly shipment figures. Yingli Green also tentatively acknowledged that the full-year shipment level would mean that the company has surpassed shipments from Suntech Power Holdings for the first time and replaced its Chinese rival as the number one module manufacturer in the PV industry in 2012.

Panasonic's PV sales in Europe remained weak in third quarter of 2012

Panasonic reported its Energy segment sales, which includes HIT PV modules of ¥142.3 billion (US$1.5 billion) for its FYQ3 2013. Energy segment sales in FYQ2 were ¥292.5 billion. Weak PV module sales in Europe were partly the reason for the sales decline, according to the company. Panasonic reported Energy segment sales for the first nine-months of ¥434.8 billion, down 6% from ¥461.8 billion in the same period a year ago. The company said that fixed cost reductions and streamlining material costs improved segment profitability ¥6.4 billion compared with a loss of ¥16.7 billion a year ago. Panasonic's overall forecast for fiscal 2013 remains unchanged from the previously revised forecast announced at the end of November, 2012.

Kyocera expects strong solar module demand in Q1

Solar module sales at Kyocera are expected to increase significantly in the first quarter of 2013, boosted by a rush to install systems before expected feed-in tariff reductions are introduced at the beginning of April. However, the Japanese electronics conglomerate is experiencing an overall demand weakness, especially from digital consumer products, forcing the company to lower revenue and profits for the year. The company does not breakout its solar module business sales. Overall, FYQ3 sales rose 13.2% to ¥318 billion (US$3.4 billion), while net income reached ¥33 billion, a 22.6% increase from the prior quarter.

Cencorp to supply conductive backsheet to Chinese PV module manufacturer

Cencorp Corporation, a Finland-based industrial automation specialist, is expected to start its first deliveries of its conductive backsheet material to new PV module manufacturing customer based in China. The company said that deliveries were expected to start in the first-half of 2013 and could generate a minimum revenue expectation of €20 million (US$26 million) over the next three years, based on a signed Memorandum of Understanding. Cencorp noted that production of the conductive backsheet material would be made at its plant in Beijing, China. The company has been active in building a technology portfolio for next generation PV module assembly. Cencorp acquired the conductive backsheet business unit of Avery Dennison in August 2012, including IP related to module manufacturing. In October last year, Cencorp acquired Sunweb Solar Energy for its IP related to MWT back contact solar cell and module assembly technology and related pilot production line.

Sharp's solar operations reduce losses on restructuring and domestic sales boost

Sharp Corporation reported PV product sales of ¥55.9 billion (US$5.9 million) for its FYQ3 2012, up 9.4% compared to the previous quarter. The company said that the increase in revenue for solar products was primarily due to increased demand within Japan that had included the domestic, commercial and utility-scale markets. Continued restructuring of its solar manufacturing operations, notably its a-Si thin-film manufacturing resulted in a decline in quarterly losses for its solar segment. Sharp reported a loss of ¥1.9 billion (US$21 million) in FY 3Q 2012, compared to a loss of ¥5.3 billion in Q2 and a ¥6.2 billion loss in the same quarter a year ago. The company reiterated that it had reduced its global headcount by about 5,400 from March 2012.

Komax Solar orders hit rock bottom in 2012; headcount reduced 50%

New orders of back-end module assembly equipment at Komax Solar declined a massive 90% in 2012 on the back of overcapacity, consolidation and capitulation of customers, especially in Asia and China. In releasing preliminary 2012 financial results Komaz Group reported total sales of approximately CHF285 million (US$305 million), down from CHF371.4 million in 2011. Komax Solar saw its order intake collapse 90% to only CHF9.0 million in 2012, compared to CHF63.7 million in 2011.

Cost cutting measures resulted in a headcount reduction of more than 50% within its solar segment during 2012, although the company highlighted that resources were secured at its US-based centre of excellence for RD&E of module assembly equipment. However, like a growing number of equipment suppliers throughout the supply chain, the company said that it did not expect business conditions in the solar industry to improve before 2014.

Module Production News Focus

Suniva to ramp module production to 24/7 operation

US-based module manufacturer, Suniva is planning to ramp its module production to a 24/7 operation. In 2011, the company had between 20-30MW of annual nameplate module capacity. The company had already been running its solar cell lines 24/7.

Although still a small player in the PV market, Suniva would seem to be benefiting from its focus on the US market, especially

Source: Suniva

Suniva is planning to ramp its module production to a 24/7 operation.

News

since import duties were imposed on Chinese-made solar cells last year.

The company also said that it OPTimus module series had gained UL 1703 1000 volt listing, a key requirement for commercial and utility-scale PV projects. The modules come in two forms – a 60-cell module with power output up to 270W and a 72-cell module with power output up to 315W.

Solar Bankers and Apollon plan 300MW production line for new low-cost CPV module

Arizona-based Solar Bankers and its German affiliate Apollon have developed a new CPV module which, the companies claim, has low production costs and a 28% conversion rate. The module, which is already patented in the US, is composed of a silicon cell and a holographic optic which is printed on a cover glass. With just a few millimetres between the cell and optic, the holographic element helps to filter the sunlight hitting the solar by selecting the more "desirable wavelengths of the light".

The module is produced using a new patented technology which enables the modules to be manufactured at significantly lower prices compared with existing technologies. Compared with existing PV modules, the new module requires just a fraction of the semiconductor material while the performance per square metre of the module surface is almost twice as high as conventional PV, the companies claim. In addition, the new module has a 28% conversion rate compared with, the companies reveal, the market average of 17%.

Kyocera Solar's North American unit reaches 2 million module milestone

PV module manufacturer Kyocera Solar's North American facilities have exceeded the two million mark in the production of photovoltaic modules. The company began manufacturing modules in North America in 2004 and has manufacturing sites in San Diego, California and Tijuana, Mexico. The modules produced have been used in residential, commercial and utility-scale projects across the Americas, Australia and other worldwide regions.

JA Solar starts production of 72-cell 215W monocrystalline modules

Volume production has started on a compact, high-efficiency monocrystalline module series at JA Solar. The 72-cell (5 inch mono cells) modules are claimed to produce a maximum power output of 215W and a mainstream power output of 210W. According to the company the modules produce an accumulated power output 3% higher than comparable models, allowing for cost savings in transportation, space and materials of over 2%.

Dow Chemical to further develop and expand capacity of ENLIGHT module encapsulant

Having recently introduced its latest ENLIGHT polyolefin PV module encapsulant films, Dow Chemical has said it will be further developing the films and adding manufacturing capacity at its integrated site in Schkopau, Germany, in 2013.

The company has previously commenced production of the films at its plant in Ohio, US, in 2010, while adding further capacity this year in Thailand.

MEMC strengthens module supply business with new 330W module

MEMC Electronic Materials has strengthened its module supply business with a new 330W module under its Silvantis brand. The MEMC Silvantis M330 PV module is the company's first product to be manufactured exclusively from its polysilicon and CCz p-type mono wafers and is designed specifically for utility-scale projects.

Cavities observed in PV modules, induced by the tabbing and stringing process

Eric Pilat[1], **Manuel Hidalgo**[2], **Dominique Thil**[2] & **Marion Vite**[1]
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ABSTRACT
A major cause of failure in PV modules is related to the penetration of the module by moisture and its retention within. The presence of moisture results in corrosion of metallic contacts or accelerates the molecular degradation of the encapsulant, causing a loss of transparency and in some cases the development of yellowing. The moisture penetration may be intrinsic to the resin itself, but most often it will occur at the interfaces. As a consequence, the adhesion of the resin to glass, metallization, cell and backsheet surfaces may be affected. Engineers involved in the assembly of PV modules used to link adhesion degradation issues to poor conditions for storing polymeric materials, especially the encapsulation resin and the backsheet. In this paper another cause, which has not yet been studied by specialists, is discussed. It is shown that the welding of copper strips can induce residues which prevent the satisfactory adhesion of the resin, resulting in delamination. This phenomenon is identified by 'spots' along the busbars after lamination. The study highlights the possible consequences of these defects for a module's performance, after consecutive thermal cycling, damp-heat and humidity-freeze testing. Recommendations are also given for choosing a suitable solder flux and optimizing the soldering process, in order to maintain satisfactory control over potential delamination problems.

Introduction

The purpose of the encapsulant is to bond or laminate together the multiple layers of a module. Additional encapsulant characteristics must include:

- high optical transmittance
- good adhesion to different module materials
- adequate mechanical compliance to accommodate stresses induced by differences in thermal expansion coefficients between glass and cells, impact and creep protection
- good dielectric properties (electrical insulation)

Over the years, various encapsulant materials have been used in modules, including polyvinyl butyral (PVB), silicone rubber and ethylene vinyl acetate (EVA); more recently, other proprietary encapsulant products have been used.

Module delamination, resulting from the loss of adhesion between the encapsulant and any other module component (glass, cells, metallic contacts, polymeric back-sheets), is a failure mechanism that needs to be addressed in order for manufacturers to achieve product lifetimes of 30–40 years [1]. A common observation has been that delamination is more frequent and more severe in hot and humid climates, sometimes occurring after less than five years of exposure. One of the first consequences of delamination is a performance loss due to optical decoupling of the encapsulant from the cells. Of greater concern, from a module lifetime perspective, is the likelihood that the void resulting from the delamination may provide a location of preference for moisture accumulation, greatly increasing the possibility of corrosion failures [2] in metallic contacts.

A chemical analysis of field-aged modules has been conducted, by comparing samples with those from unexposed modules; this analysis provided strong evidence of the dynamic chemical interactions occurring in the module during field exposure. It is clear that sunlight, temperature, oxygen penetration and moisture migration through the encapsulant provided the ingredients required for a variety of chemical reactions, many of which may degrade the integrity of the encapsulant's adhesive bond to the cell. Typical reactive materials found at the cell/encapsulant interface after extended field exposure are phosphorus, titanium, oxygen, solder flux, encapsulant additives and even sodium that has migrated through the encapsulant from the glass.

> "Corrosion is the consequence of interactions between water, ionic species and oxygen."

One of the major concerns for module durability is corrosion, because it can reduce the power output of a module by increasing the resistance at the electrical interconnections. Corrosion is the consequence of interactions between water, ionic species and oxygen. Protection against corrosion involves a combination

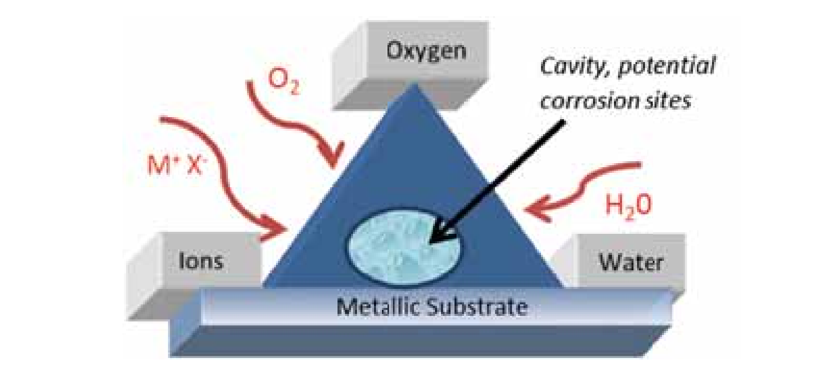

Figure 1. Corrosion triangle (adapted from Ketola & Norris [2]).

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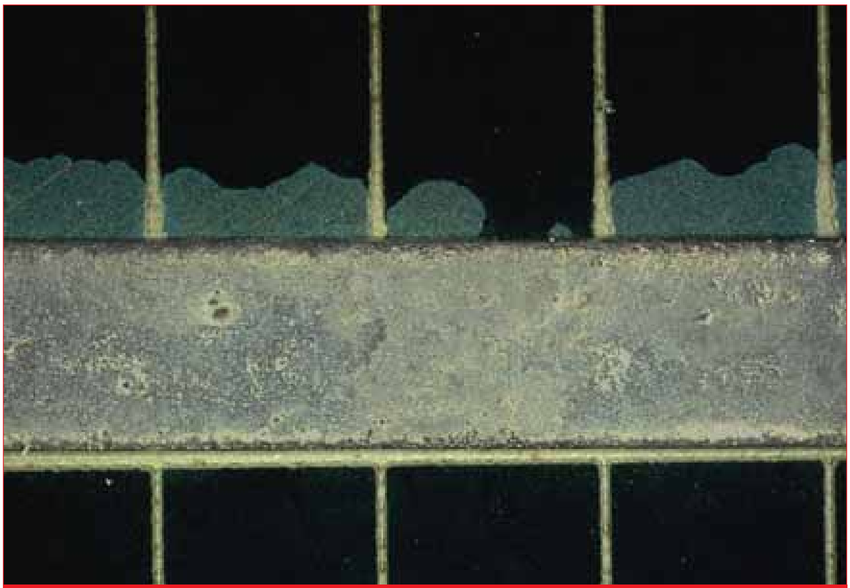

Figure 2. Greenish spots along the tinned-copper ribbon.

Figure 3. Defect observed using 100× magnification.

of effects: low moisture permeation is only one factor that influences this protection. Indeed, moisture permeability – or water vapour transmission rate (WVTR) – should be minimized, but this might not be the only determining factor in corrosion protection, and ultimately in the long-term performance of electronic devices. This fact has been known to the electronics industry for decades and can be related to the corrosion triangle shown in Fig. 1 [3].

Water needs to be in the liquid state to allow the potentially ionic material to ionize into its cathodic and anodic components. Ionic species can be created as a result of contamination or degradation of the encapsulant itself. On the other hand, oxygen is typically present, unless the atmosphere is inert or has been evacuated, and even if this was the case during module manufacturing, oxygen can easily permeate back into the module.

It is known that when EVA is exposed to UV radiation and high temperatures, it may be subject to deacetylation, in accordance with the widely accepted Norrish II mechanism, which results in the formation of acetic acid. Moreover, water and oxygen can increase the chances of this reaction occurring, by (for instance) lowering its activation energy [4]. Thus, damp-heat conditions can very likely lead to an increased release of acetic acid, a product which favours metallic corrosion. Moreover, it should be noted that EVA uses peroxide radical initiators, which lead to the desired EVA cross-linking, and some peroxides can generate acidic by-products. Taking into account all the previously mentioned parameters, any void must therefore be seriously considered to be a potential cause of eventual degradation.

Inspection

Optical

Chapter 10.1 of the IEC 61215 standard specifies that each module should be inspected carefully with illumination greater than or equal to 1000 lux. Only ten criteria are defined, and the last one is rather vague: "Any other condition that may affect performance". On top of that, if the inspection is performed without any magnification, small visual defects that could affect performance may not always be visible.

In the present paper, the focus will be on one defect which can be observed in c-Si modules, although this type of defect is not excluded from also appearing in PV modules using thin-film technologies. The defects have the appearance of small spots along the tinned-copper ribbon (Fig. 2), but very often they cannot be seen when no lens magnification is used.

Spots may be large enough to be seen by the naked eye, as in the photo in Fig. 2, but more often than not one has to look carefully with an optical microscope (Fig. 3) in order to detect them (100× magnification is more than enough).

X-ray probing

X-ray inspection can reveal the presence of some materials such as silver or tin. In

(a) (b)

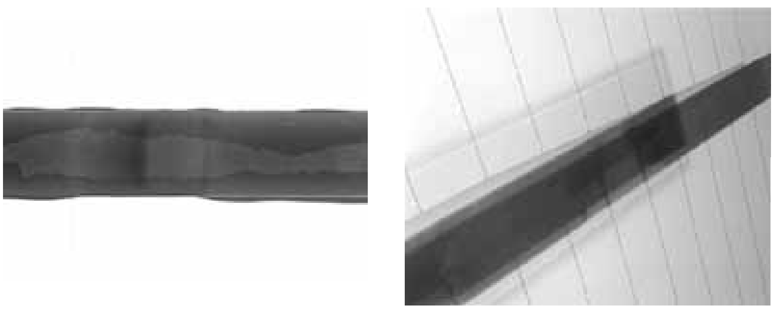

Figure 4. X-ray images: (a) view from above of the copper ribbons soldered to the cell; (b) view of the copper ribbons from an angle.

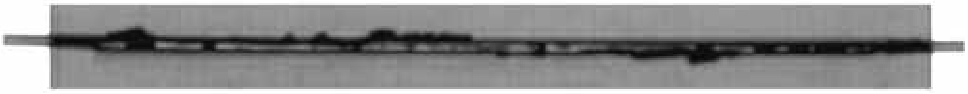

Figure 5. Acoustic image by transmission from the top.

Figure 6. Correlation between the emission C-scan multigate mode and transmission mode.

this study, the defect areas were inspected using 10× magnification (Fig. 4). A lack of welding is observed in the centre of the ribbons, but there are no black areas corresponding to the locations of the previously mentioned defects.

> "Acoustic micro-imaging combining emission and transmission modes is a rapid and non-destructive tool for identifying the location of cavities."

Acoustic micro-imaging

Acoustic micro-imaging combining emission and transmission modes is a rapid and non-destructive tool for identifying the location of cavities. The examination of a cell using this type of microscopy can reveal differences in acoustic impedance of the structure and thus allow the detection of signs of delamination, defects, decrease in adhesion, etc. The approach adopted for examining a cell by acoustic micro-imaging is as follows: an initial assessment of the connectors is conducted in transmission mode (Fig. 5), to examine the most critical part of the cell and to try to detect the optically observed signs; a second series of examinations is then carried out, again in transmission mode, over the entire cell, to verify the presence or absence of such defects elsewhere. If acoustic detection of the optically observed defects is successful, the goal is ultimately to study their location as a function of the thickness of the encapsulant–metal joint, and to analyze the nature of this information. The emission mode of acoustic analysis is then used, employing a multigate method (C-scan comprising a multitude of doors, allowing a layer-by-layer imaging of the structure as a function of thickness). In this way a correlation between the spots – i.e. the 'suspicious areas' – visible through optical means and their detection by acoustic emission is established. Finally, transmission acoustics are used to find proof that the defects are caused by delamination (Fig. 6).

From the acoustic analysis (supplied by the Predictive Image team) it is known that

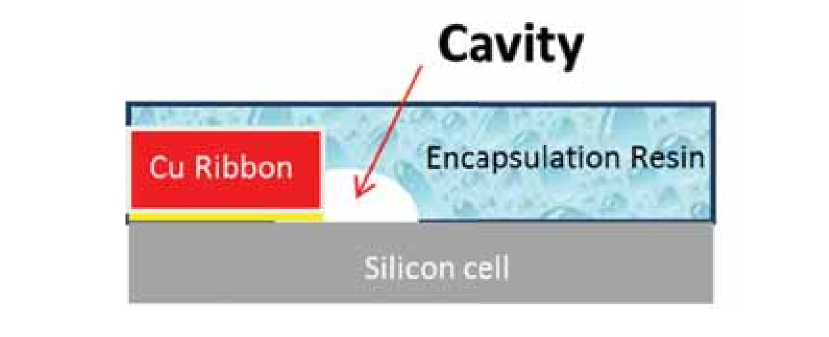

Figure 7. Location of a void, detected by acoustic analysis.

the defect is a cavity, or a void, and that it is located at the base of the connectors, as shown in Fig. 7.

Experimental

The tendency for voids to form inside the resin located at the base of the connectors can be either increased or reduced, depending on different manufacturing practices and conditions. Some of the factors that might influence the presence or absence of these voids will be mentioned here.

In the case of a thermoplastic encapsulant, the influence of the laminator's thermal profile was studied. First of all, the degassing time at the beginning of the lamination cycle, and the actual lamination time at a temperature higher than the melt temperature of the thermoplastic encapsulant, was varied. No resulting correlation with the presence of void defects was identified. Next, the actual lamination temperature was increased; the result was better, but there were still some voids. After the lamination step, the module was heated in an oven at 95°C. When the module was hot, the defects completely disappeared but gradually returned upon cooling.

The same process was then performed on two different cells provided by two different cell manufacturers. Although one of these produced better results than the other, voids occurred in both cases. It is important to note that, as stated earlier, void detection can sometimes be carried out by visual inspection under adequate illumination conditions, but in order to be sure that there are no defects, an optical enhancement must be performed using a microscope.

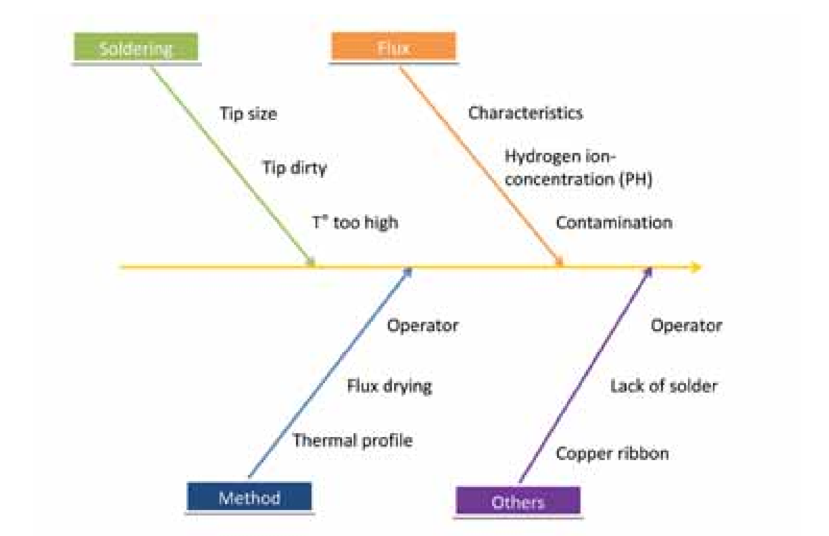

Figure 8. Fault tree analysis.

	No-clean flux remover	Brush-clean	Water 60°C & UL	No-clean
No-clean flux 1	1/1			3/6
No-clean flux 2	0/1			0/3
No-clean tacky flux		1/1		1/3
Water-soluble flux			0/1	

Table 1. Number of busbars with defects vs. total number of busbars with same flux and cleaning process.

The next step was to produce modules from PV cells that had been previously cleaned with acetone before soldering, or by carefully cleaning the connectors with acetone after soldering. This did not result in any significant improvement in respect of the presence of voids. It was noted that the problem became worse when the cells had been stored for a long time before the soldering process and fabrication of the module.

Taking into account these experimental results, an FMECA approach (failure modes, effects and criticality analysis) was followed. In the fault tree analysis, four families were identified (Fig. 8). From this analysis, and the previous results with the thermoplastic encapsulant, it became clear that the soldering step could be a major contributor to the presence of defects.

> "It became clear that the soldering step could be a major contributor to the presence of defects."

It was then decided to produce some mini-modules in order to identify the main issue. The first module was made using two cells, comprising two busbars per cell. Different configurations regarding the connector ribbons were considered for each busbar:

- Configuration 1: The soldering flux was applied to the cell's silver bar (busbar), and the connecting copper ribbon was laid upon it without soldering.
- Configuration 2: The soldering flux was applied to the cell's silver bar, and the copper ribbon was also dipped in flux. The ribbon was soldered onto the silver bar.
- Configuration 3: The soldering flux was applied to the cell's silver bar and the hot soldering iron passed over it. This enhanced the temperature effect of the soldering step.
- Configuration 4: The soldering flux was applied to the cell's silver bar, and the ribbon (without flux dipping) was soldered onto the silver bar.

The spots appeared only in the case of configuration 2, clearly showing the influence of the soldering step conditions.

A second module was then produced by placing two cells with three busbars in each of the following configurations:

- Configuration 1: The copper ribbon was dipped in flux and soldered onto the silver bar.

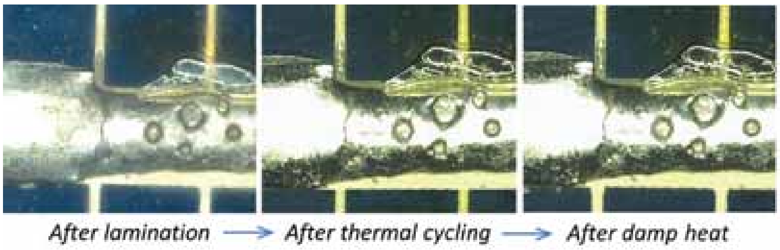

Figure 9. Visual inspection (50× magnification) of the same defect before and after ageing.

	Variation of maximum power after test [%]			
	Reference	Module 1	Module 2	Module 3
TC	1.1	0.1	–0.7	–0.7
TC and DH	1.3	–3.7	–8.8	–3.4
TC, DH and HF	1.6	–9.9	–21.6	–13.4

Table 2. Evolution of maximum power (flash-test measurements) after ageing tests, for the three modules containing defects, compared with the reference module with no defects.

- Configuration 2: The copper ribbon was dipped in flux and heated with the soldering iron. The ribbon was then laid on the cell's fingers without any actual soldering.
- Configuration 3: The copper ribbon was dipped in flux and heated with the soldering iron. The ribbon was then laid on the silver bar of the cell without any actual soldering.
- Configuration 4: The copper ribbon was placed on the silver bar without any flux, heating or soldering.
- Configuration 5: The copper ribbon was simply laid upon the cell's fingers without any flux, heating or soldering.
- Configuration 6: The copper ribbon was dipped in flux and then laid upon the silver bar of the cell without any heating or soldering.

These experiments confirmed that spots appeared when the copper ribbon was dipped in flux and then heat soldered upon the silver busbar of the cell.

Up to this point, it had become apparent that the defects could be created by the soldering step (no defects if the ribbons were not soldered), and that the presence of the soldering flux was necessary to their appearing. The decision was therefore taken to investigate the influence of different types of soldering flux.

Modules were produced with different kinds of soldering flux, with or without a post-soldering cleaning step to evacuate flux residues. The busbars containing defects were identified, with respect to the flux employed and the cleaning process used after soldering, as shown in Table 1.

With no-clean flux 1, defects appeared even when the soldered ribbon was cleaned with the alcohol-based no-clean flux remover. With no-clean flux 2, no defects were detected, even without cleaning; with the no-clean tacky flux, defects appeared. In the case of the water-soluble flux combined with cleaning in a heated ultrasonic bath, no defects were observed. The defects were caused by the presence of flux residues, which can be generated even when the so-called 'no-clean' fluxes are employed. The nature of the flux is an important factor.

> "The defects were caused by the presence of flux residues, which can be generated even when the so-called 'no-clean' fluxes are employed."

The voids seem to be caused by encapsulant delamination at places where the presence of flux residues hampers adhesion. One assumption is that flux is burned during the soldering process and that the soldering iron sweeps and pushes the solid residues. These residues concentrate in one location and prevent good adhesion of the encapsulant to the cell or to the silver metallization. The nature of the flux seems to be an important factor, as no-clean flux 2 did not produce any defects.

The authors' latest experimental work has revealed that voids may also be created in EVA-encapsulated modules, and that the soldering step – including the soldering flux influence – may be at the heart of these defects. The possible consequences of these voids for reliability issues of EVA-encapsulated modules will be discussed in the next section.

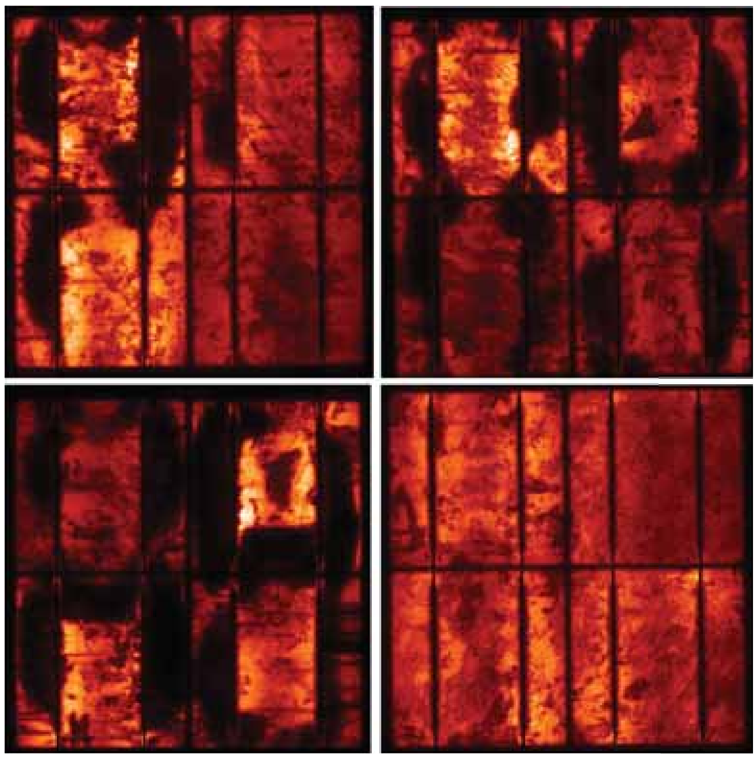

Figure 10. EL imaging of three different modules after ageing (TC, DH and HF), compared with the reference module at bottom right.

Impact on module reliability

Consecutive thermal cycling (TC), damp-heat (DH) and humidity-freeze (HF) tests were conducted on a series of three modules in which the defects described here were abundant. (In fact, once the origin of the problem became clear, an emphasis was placed on the conditions leading to the manifestation of defects, mainly flux type and quality, but also volume of flux dispensed and soldering temperature.) For each test, the conditions described in the IEC 61215 standard were followed, and the tests were conducted consecutively in the order given above (TC, DH, HF). For comparison, a module containing no such defects was included in the test panel.

Fig. 9 shows photographs (from optical microscopy at 50× magnification) of such defects (i) after lamination, (ii) after TC testing (> 200 cycles), and (iii) after DH testing (> 1000 hours). As can be seen from these images, there is no apparent evolution of the voids as a result of the TC and DH ageing tests. Inspections were carried out at different locations where the voids were present.

However, there was a clear performance decline (as measured by the maximum power of the modules tested at STC with a flash-type solar simulator from PASAN) after each ageing test, with respect to the reference module containing no defects (see Table 2).

Moreover, after the HF tests on the modules (which had already undergone TC and DH testing), a massive degradation, mostly detectable through electroluminescence imaging (using GREAT EYES EL equipment), became evident in all the modules exhibiting voids (see Fig. 10). This was definitely not the case for the reference module without the void defects. Further investigations need to be conducted in order to find out if there is indeed a link between this massive degradation and the void defects discussed in this paper.

Possible solutions

Once the problem had become apparent and its origin had been identified (see previous sections), possible solutions were explored. The soldering flux, having been identified as the main factor, was investigated further. Experiments were conducted while carefully monitoring the flux quality, and especially its concentration as measured by the pH method, which reflects the actual concentration of the product. It was found that fluxes for which the concentration has become too high during production may lead to a higher number of defects. Nonetheless, with some fluxes kept at the right concentration, there were still some defects, although clearly not as many.

A thorough screening of fluxes of different natures was then carried out, which seemed to be the most robust solution to the problem. It was discovered that the choice of flux is the most important preventive action against the creation of voids in modules with different encapsulants.

“The choice of flux is the most important preventive action against the creation of voids in modules with different encapsulants.”

Summary

To avoid the issue of bad adhesion due to flux residues, the soldering process must be carefully controlled, especially with regard to the nature of the flux and its quality (concentration), as well as the volume dispensed. In the case of small-volume production, or if the process is not automated, it is highly recommended to either use water-soluble fluxes and clean the cells after soldering the copper band before encapsulation, or to carefully choose the no-clean flux to be employed, by checking, with the help of an optical microscope, the absence of voids due to delamination.

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About the Authors

Eric Pilat graduated as an engineer from INSA of Lyon in 1984. He has more than 12 years’ experience in the packaging of microelectronic components, MEM and CCD devices. In 1997 he founded a company for developing an innovative process for manufacturing connections for high-density electronics. Eric joined CEA in 2008 to begin development of the platform for PV modules.

Manuel Hidalgo earned his Ph.D. degree in macromolecular materials from the University of Lyon 1. He is a senior research scientist for Arkema and currently a co-project leader at Sollia, a joint laboratory with the French Institute for Solar Energy (INES). Dr. Hidalgo holds more than 50 patents and has published almost 30 papers in the polymer field.

Dominique Thil has been working in R&D since 1990, mainly in the chemical process industry. At present, he works at the Sollia joint laboratory within INES. Dominique has two years’ experience in the manufacturing of PV modules, including soldering and lamination.

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Overview of PV module encapsulation materials

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ABSTRACT
The rapid growth of the PV market during the last five to seven years entailed a considerable expansion of the encapsulation material market, which temporarily led to shortages in the supply chain. Simultaneously, module prices decreased significantly, which resulted in intense pressure on production costs and the cost of PV module components, inducing changes in the encapsulation material market towards new materials and suppliers. This pressure – together with the huge impact of the encapsulation material on module efficiency, stability and reliability – makes the selection of encapsulation technologies and materials a very important and critical decision in the module design process. This paper presents an overview of the different materials currently on the market, the general requirements of PV module encapsulation materials, and the interactions of these materials with other module components.

Introduction

PV module set-up

Crystalline silicon (c-Si) PV modules typically consist of a solar glass front cover, a polymeric encapsulation layer, mono- or polycrystalline silicon cells with a metallization on the front and rear, solder bonds which electrically connect the individual cells, and a polymeric (or, less commonly, glass) backsheet.

Thin-film PV modules may be manufactured either via a substrate process, where the semi-conducting layers are processed on the module rear cover, or via a superstrate process, where processing occurs on the front cover (Fig. 1(b) and (c)).

The major requirements of providing mechanical stability, high transparency in the spectral response range of the solar cell and protection of the cell and metallization against exterior impacts make the use of solar glass for front-cover material the most obvious choice. For flexible technologies, polymeric front sheets are also used, which have to provide good barrier properties. Rear materials are also expected to provide mechanical stability, electrical safety, and protection of the cells and other module components from exterior impacts.

Production process

A standard module production process consists of the following steps: glass washing and drying; tabbing of the cell ribbons and soldering of the cell matrix; module lay-up, including soldering of the cross connection; embedding; edge sealing and framing; attachment of the junction box; and a power measurement.

In general there are three different process types for embedding the cell matrix into the surrounding materials. The most common is the vacuum lamination process, which is used primarily for ethylene vinyl acetate (EVA) encapsulants, but also for a range of thermoplastic films. Another possibility, for thin-film devices, is a roll-to-roll laminator combined with an autoclave – a well-known concept in the glass industry. An alternative to the lamination process is the use of cast resins, for example silicones. In a c-Si module process, the liquid encapsulation material has to be dispensed in two steps: first to the top of the glass and second to the applied cell matrix.

Of the various module production steps, the embedding process requires the longest cycle time. The main goal of equipment producers is to decrease the process time by developing laminators which process more modules at the same time. Another option is to modify the encapsulant itself by adding optimized peroxide cross-linking agents to achieve a faster cross-linking or by using thermoplastic encapsulants.

"The main challenge in all embedding processes is to achieve uniform and sufficient curing or cross-linking levels to ensure strong adhesion and stable laminates."

The main challenge in all embedding processes is to achieve uniform and sufficient curing or cross-linking levels to ensure strong adhesion and stable laminates. Consequently, the equipment

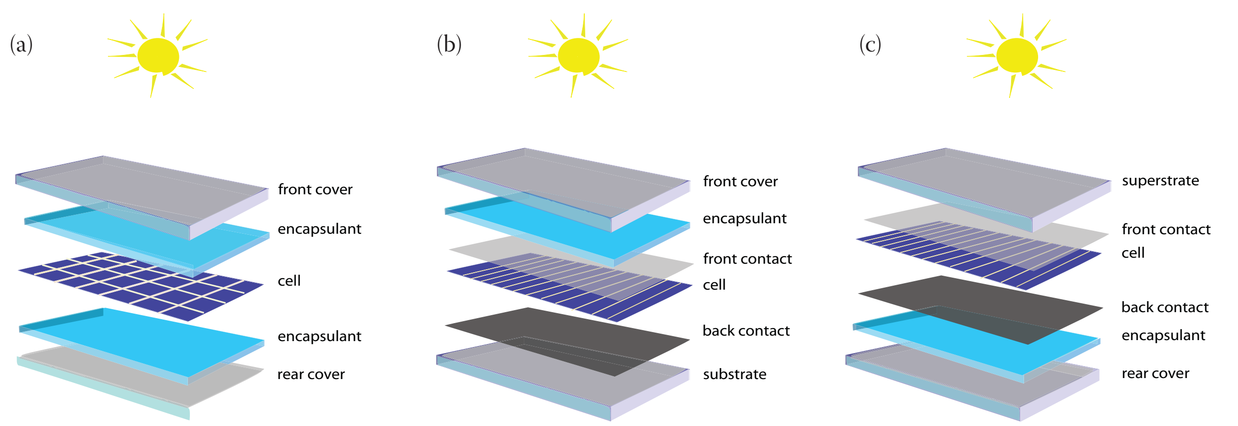

Figure 1. (a) General set-up of a c-Si PV module; (b) substrate-type thin-film PV module; (c) superstrate-type thin-film PV module.

must provide excellent heat and pressure uniformity, a high accuracy in temperature control, and long-term stability of the process parameters.

Loss mechanisms and interactions with other components regarding module efficiency

The cell-to-module (CTM) efficiency ratio can be defined as the efficiency of an interconnected cell matrix, measured within a module lay-up in relation to the average cell efficiency measured in contact with air. The CTM value strongly depends on the embedded cell type. For a highly efficient solar cell with a homogeneous anti-reflective texture and high response in the blue light spectrum, the CTM loss is usually higher than that of a low-efficiency cell embedded in the same module materials.

From cell to module, there are several factors affecting efficiency, mostly with a negative impact. These factors are losses due to inactive areas in the module, which only affect the module efficiency and not the actual power output. Factors that influence power output can be separated into optical and electrical effects; the electrical losses arise mainly from serial resistance losses within the cell interconnections.

Several interacting optical effects can be observed after encapsulation (Fig. 2). First, reflection losses occur at every material interface where the refractive index changes. Second, there are absorption losses in every module layer located in front of the cells. The reflected light from the cell surface, which includes the finger area and the busbar or ribbon area, can be partially or totally redirected to the cell. By using a highly reflective backsheet, incident radiation in the cell gap is scattered backwards. If it hits the first interface of the module, usually glass–air, it is partially or totally reflected, depending on the incidence angle. Some of this radiation then hits the cells in their active area and increases cell current and power output. For the embedding materials it is most important to achieve negligible absorption in the relevant section of the spectral response (350–1200nm for c-Si technology).

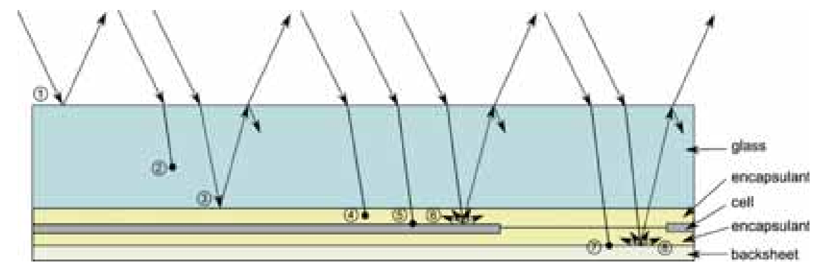

Figure 2. Optical losses in a c-Si PV module [1].

There are various loss mechanisms which reduce the amount of light reaching the cell. These mechanisms (indicated in Fig. 2) are:

- ①,③ reflection losses at the air–front and front–encapsulant interfaces;
- ②,④ absorption losses in the front and encapsulation material;
- ⑤ absorption of the cell;
- ⑥ reflection of the cell surface, and partial or total re-reflection at the front–air interface;
- ⑦ absorption of the backsheet material;
- ⑧ reflection of the backsheet material, and partial or total re-reflection at the glass–air surface.

The refractive index of the encapsulant influences the reflection losses at the glass–encapsulant interface and at the silicon–anti-reflective coating (ARC)–encapsulant interface. The optical gain due to optical coupling becomes less relevant for a cell with an efficient light-trapping texture and ARC.

Properties of encapsulation materials

Requirements for encapsulation materials

The requirements for PV module encapsulants in terms of optimizing module efficiency can be divided into five categories: electric yield, electrical safety, reliability, module processing and cost.

- The encapsulant has to provide low light absorption and an adapted refractive index to minimize interface reflectance.
- A high thermal conductivity reduces operating temperatures and thus improves electric yield.
- For electrical safety, only very low leakage currents are allowed by standard type-approval testing in accordance with IEC 61215.
- In terms of PV module reliability, the encapsulant properties are critical in respect of UV irradiation, humidity, temperature cycles, extremely low or high ambient temperatures, mechanical loads, electric potential relative to ground, etc. The encapsulant has to maintain strong adhesion to the other module components and protect the cell and metallization from external impacts.
- A module manufacturer will also look at material cost, processing cost and processing time, shelf life and quality assurance issues.

Parameters and methods for evaluating encapsulation material

On the basis of the requirements stated above, there are several crucial parameters which have to be taken into account when choosing a suitable PV encapsulant (see Table 1). Besides basic material properties – such as glass transition or melting temperature, which can be determined by characterization techniques like differential scanning calorimetry (DSC) or dynamic mechanical analysis

Parameter	Method	Relevance
Glass transition temperature T_G	DSC, DMA, etc.	Limited variation in material properties within the temperature range of exposure
Melting temperature T_M	DSC, DMS, etc.	Processability
Young's modulus E	DMA, tensile testing	Mechanical stress on cell
Refractive index n	Refractometry	Minimizing optical losses
Absorption	Fourier transform spectroscopy	Minimizing optical losses
Volume resistivity	Resistivity test	Electrical insulation
WVTR OTR	Permeation measurements	Knowledge about mass transport processes within the module

Table 1. Overview of the most important aspects of encapsulation evaluation.

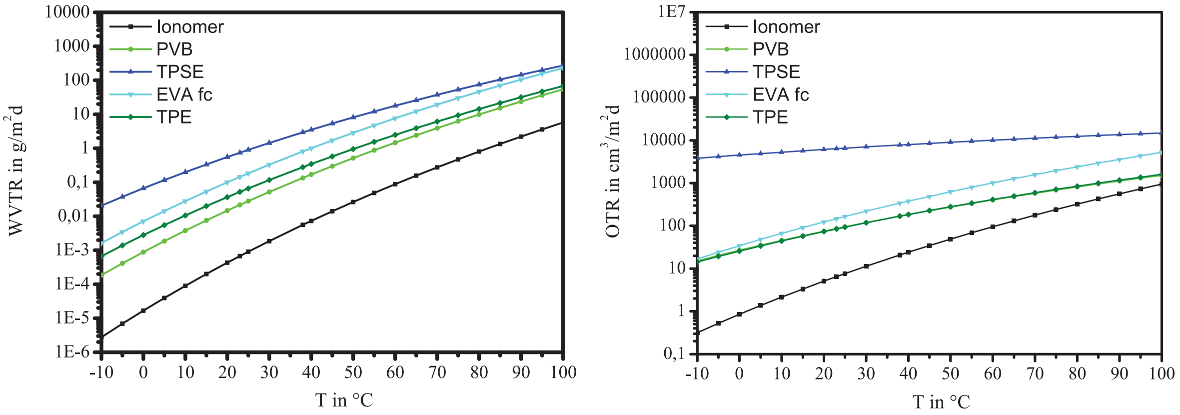

Figure 3. Temperature dependency of WVTR and OTR for different encapsulation materials [3].

PV Modules

(DMA) – the mechanical properties are also very important in order to achieve buffering properties to withstand mechanical impacts and mechanical and thermomechanical loads.

Important factors influencing a PV module's durability are the diffusion properties of the backsheet and the encapsulation material with regard to gases such as oxygen or water vapour [2]; both of these can accelerate degradation reactions by penetrating the PV module through the surface of the polymeric backsheet and by diffusing through the encapsulation polymer until they reach the area between the solar cell and the front glass. A commonly neglected fact is the significant dependency of the water vapour transmission rate (WVTR) and the oxygen transmission rate (OTR) of an encapsulant on the temperature. Since permeation processes are greatly accelerated by the temperature, as shown in Fig. 3, particularly high transmission rates at high temperatures result in rapid inward and outward mass transport processes of the module.

Another interesting tool for material characterization and evaluation is Raman Spectroscopy – this has recently been reported as a quick and non-destructive method for analyzing the encapsulation degradation of small test laminates or full-size PV modules [4].

Encapsulation materials

Market survey

In the 60s and 70s, mainly polydimethylsiloxane (PDMS) was used for the encapsulation of the first PV modules. This has since been replaced by other materials such as EVA, which has now dominated the market for several decades. All the polymers used are thermoplastic materials or elastomers; the latter, however, require cross-linking during the lamination process, which increases the cycling times and production costs. The need to reduce the costs of PV modules opens the market for new encapsulation materials, although reliability risks must be considered to be critical, given the long-lasting performance guarantees that PV manufacturers have to offer for their PV modules.

> "The need to reduce the costs of PV modules opens the market for new encapsulation materials."

The growth of the PV market in recent years has led to an increase in the number of suppliers of EVA-based materials. In parallel, the number of non-EVA materials has also increased during the last few years: nine companies with 23 non-EVA products have been documented [5]. Yet, despite all the different polymers in use, the PV market – compared to the total annual production volume – is still a niche market for suppliers of base polymers. Manufacture of the compounds is therefore usually done by smaller companies. Fig. 4 shows the number of products in each of the different material categories.

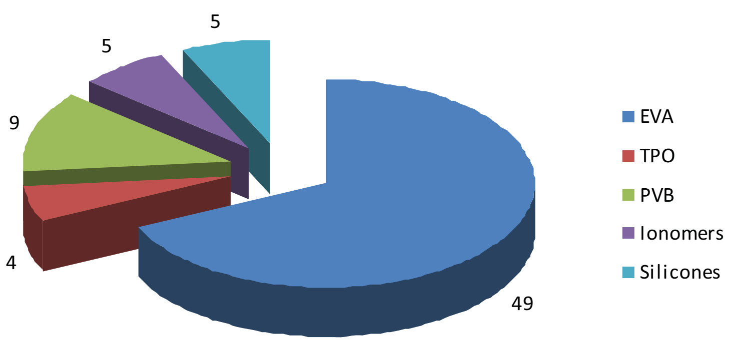

Figure 4. Number of products in the different materials [5].

Material properties and stability

The encapsulation materials can be divided into 1) non-cross-linking thermoplastic or thermoplastic elastomeric (TPE) materials, and 2) elastomeric materials; the latter form covalent bonds between the polymer chains. The most widely used encapsulation material, EVA, and two-component silicone and urethane (TPU) materials have to be subjected to a cross-linking process which can be induced by high temperature levels or UV irradiation or via a chemical reaction (two-component systems). The thermoplastic or TPE materials polyvinyl butyral, TPSE and ionomers, as well as modified polyolefines (PO), melt during the module manufacturing process without forming chemical bonds between the polymer chains (cross-linking).

EVA

The copolymer EVA is the most popular PV module encapsulant worldwide and has been used in the PV industry for more than twenty years. Over this long period of time, the durability of PV EVA, which is highly influenced by the additive formulation used, has been improved tremendously, especially with regard to the degradation problem of discoloration (yellowing) [6,7]. This yellowing phenomenon, which has been described extensively for the first PV plants, is most likely caused by the photothermal degradation of additives such as UV light stabilizers, UV absorbers and antioxidants [8,9]. Besides additive decomposition, the main degradation reactions of EVA are

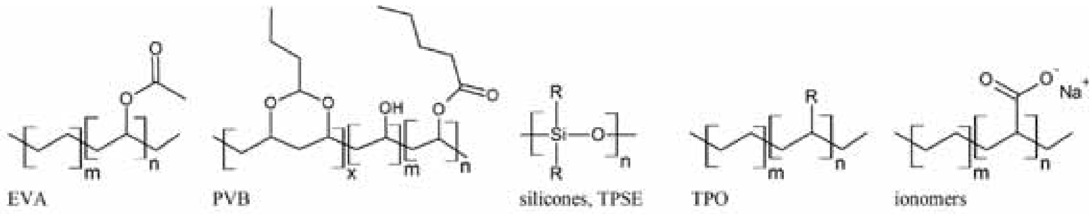

Figure 5. Chemical structures of the most common PV module encapsulation materials.

Polymer	Polymer type	Parameter			
		T_G [°C]	*E* [MPa]	Refractive index (*n*)	Volume resistivity @ 23°C [Ωcm]
EVA	Elastomer	–40 to –34	≤ 68	1.48 to 1.49	10^{14}
Silicone		–50	≤ 10	1.38 to 1.58	10^{14} to 10^{15}
PVB	Thermoplastic	+12 to +20	≤ 11	1.48	10^{10} to 10^{12}
Ionomer		+40 to +50	≤ 300	1.49	10^{16}
TPSE	Thermoplastic elastomer	–100	≤ 280	1.42	10^{16}
TPO		–60 to –40	≤ 32	1.48	10^{14} to 10^{18}

Table 2. Overview of typical physical properties of different encapsulation materials.

deacetylation, hydrolysis and photothermal decomposition [6], which may lead to the evolution of corrosive degradation by-products, especially acetic acid. These by-products in turn may accelerate metallization corrosion.

Initially a thermoplastic material, EVA can be transformed into an elastomer by the utilization of cross-linking additives activated by high temperatures or UV irradiation. This cross-linking reaction is challenging not only in terms of module processing time, but also in respect of material storage (volatilization of cross-linking agents) and quality management (determination of the degree of cross-linking by Soxhlet extraction).

Polyvinyl butyral (PVB)

PVB is a thermoplastic polymer which has been used since the early 80s as a PV module encapsulant. It represents the second most processed encapsulation material, with similar material costs to EVA.

In contrast to other encapsulation materials, PVB is very sensitive to hydrolysis because of a higher water uptake; it therefore has to be combined with a low WVTR backsheet [2]. Plasticizers are added to PVBs to improve their mechanical processability and to modify their phase-transition temperatures [10]. Advantages over EVA are better UV stability and better adhesion to glass. The UV transparency is almost as good as that of EVA. The lamination processing time can be reduced by about 50% compared with EVA [11].

The processing of PVB initially required the application of an autoclave because of the high pressure and temperature needed, but new PVB formulations allow standard lamination processes to be used. The main applications of PVB in the photovoltaic industry are building-integrated photovoltaics (BIPV) and thin-film technology with a glass–glass configuration.

Silicones

Silicones are mixed inorganic–organic polymers which include the elements silicon, carbon, hydrogen and oxygen as the main constituents. Although very promising as a PV encapsulation material, silicone is only rarely used owing to the high price and the need for special processing machines (and techniques). Silicones are most often used in special application fields demanding very high quality, for example extraterrestrial applications.

Because of their chemical properties, silicones have excellent resistance to oxygen, ozone and UV light. Other advantages of silicone are a wide temperature stability range (–100°C to 250°C) and excellent transparency in the UV-visible wavelength range. The low Young's modulus and glass transition temperature values (see Table 2) also mean that silicone is highly resistant to mechanical stress. The refractive index of silicones can be modified between 1.38 and 1.58 by the variation of chemical groups at the silicon atom. Because of the low moisture uptake (< 0.05%), silicone encapsulants are very insensitive to moisture, making them extremely interesting for use in optical and optoelectronic applications [12].

Thermoplastic silicone elastomer (TPSE)

TPSE represents a relatively new encapsulant class combining superior silicone performance and thermoplastic processability, but, because of the relatively high price, is currently only used in special applications. The fast curing and additive-free physical cross-linking of TPSE encapsulants, combined with their excellent mechanical properties without the use of plasticizers, make them promising candidates for continuous lamination processing [13].

Since the cross-linking is performed via hydrogen bonds, TPSE-based PV modules may be recycled more easily than EVA-based modules. TPSE shows good UV resistance and visible light transmission and can be used over a wide temperature range (–80°C to 100°C). Furthermore, TPSE encapsulants have good electrical insulation properties (see Table 2) and are highly water repellent.

Thermoplastic polyolefin elastomer (TPO)

TPO is a polymer blend consisting of thermoplastic polyolefins (e.g. polyethylene and polypropylene) and olefinic elastomers (e.g. ethylene-propylene rubber and ethylene-octene rubber). Often used in the automobile and building industry in the past [14], TPO is an interesting candidate for PV encapsulation because of its low price. The material has a high electrical resistivity, does not degrade under acetic acid formation and is resistant to hydrolysis, although the water permeation of TPO is significantly higher than that of EVA.

Ionomers

Ionomers, more specifically ethylene ionomers, belong to the category of thermoplastic encapsulant materials and are produced from ethylene and unsaturated carboxylic acid co-monomers (e.g. ethylene-methacrylic acid copolymer EMAA). In the solar industry, ionomers

Polymer	Condition		
	Equipment	$T_{processing}$ [°C]	$t_{processing}$ [min]
EVA	Vacuum laminator	140–160	8–20
Silicone [27]	Casting process, dispenser	80	30
PVB [28]	Vacuum laminator, roll lamination and autoclave	140–160	8–20
Ionomer [29]	Vacuum laminator	140–160	10
TPSE [30]	Vacuum laminator, roll lamination and autoclave	160–170	7–10
TPO [31]	Vacuum laminator	140–160	10–14

Table 3. Overview of processing conditions for selected materials.

represent a different class of encapsulation materials, with high production costs. The good UV stability of ionomers has already been demonstrated in architectural applications in the last 15 years [15]. Ionomers are also used as encapsulants in wire and cable applications [15].

A physical cross-linking between the ionic components of the polymer is automatically induced during the synthesis and does not require any extra steps for a (chemical) cross-linking as in the case of EVA processing. Furthermore, no formation of acetic acid is observed during weathering [16] and a much longer shelf life is achieved (up to three years) [17]. During the last two years the focus of ionomer research has been on thin-film solar technology, because of the highly improved moisture sensitivity and lower WVTR compared with EVA [18]. The first frameless CIGS modules with incorporated ionomers have recently been realized [19]. The enhanced adhesion of ionomers to backsheets also allows their prospective use in c-Si technology [20]. Ionomers demonstrate high volume resistance and a high degree of mechanical stability (see Table 2).

The processing temperature and time for selected encapsulants are shown in Table 3. With certain materials, the parameters vary over a broad range and can be modified by the addition of special additives. When two-component silicones are cured, the processing time and temperature can differ as a result of using different catalysts, leading to curing times of 5–50 minutes and processing temperatures between room temperature and 120°C.

Interactions with other PV module components

The corrosion of inorganic PV module components (i.e. the metallization) is, besides polymer degradation, one of the most important aspects of PV module degradation. Significant decreases in PV module performance are caused by the corrosion of the cell (e.g. of the anti-reflective coating) or the corrosion of the grid, the solder bonds and the rear metallization [21,22]. Since EVA degradation may be accompanied by the formation of corrosive by-products, such as acetic acid, the metallization corrosion can thereby be accelerated [23,24]. In addition, water ingress facilitates the delamination of EVA from the cell [25] and therefore grid corrosion [26].

New cell and module designs and their impact on PV module requirements

High-efficiency crystalline solar cells (μ > 19.0%) achieve their high power output by, among other things, increasing the spectral response in the blue/UV light spectrum. It therefore becomes more important to shift the UV cut-off of the encapsulants to below 350nm, which can lead to a relative power increase of more than 1%.

Another requirement relates to the reduction of the module weight by using thinner front glass or by even replacing it with rigid polymeric layers. In the case of the latter, encapsulants have to be modified in order to obtain a good adhesion to these alternative materials, for example polymethyl methacrylate (PMMA). If the rigid layer is transferred to the back side of the module, a wide range of material groups can be used, starting with glass-fibre materials or even structured aluminium alloys. The front side can be covered with a polymer film that has high light transmittance, such as ethylene tetrafluoroethylene (ETFE). Whenever the situation of embedding brittle solar cells using polymeric materials arises, the mismatch of thermal expansions has to be damped by a more compliant encapsulant.

A new cell technology which is presented on R&D platforms involves the use of copper-metallized crystalline solar cells. Common encapsulants therefore have to be verified in respect of their chemical reactivity with copper.

Conclusion and perspectives

Because of the strong influence of the encapsulation material on efficiency and reliability, the selection of an appropriate material is an important aspect in module design. With regard to durability and safety, encapsulants have to fulfil very demanding requirements over long periods of time in various climatic and operational conditions. For the polymeric materials used, the microclimatic conditions are crucial in those degradation processes which are strongly influenced by other materials in the modules, especially the front and rear materials. Thus the selection of an adapted combination of materials for encapsulation is absolutely vital.

In addition to the described technical requirements, there is an increasing economic pressure on the module market and therefore on production costs. On the one hand, improved transmission properties in the UV range are required, and on the other hand, materials allowing faster production processes need to be taken into account in order to reduce manufacturing costs. In view of the long warranty periods given by module manufacturers, which restrict the introduction of new materials or production processes, only a few types of material are being considered. Although EVA still dominates the market, mainly because of its good cost–performance ratio and the decades of experience gained from its use, the number of other encapsulation materials and types has nevertheless increased significantly.

Acknowledgements

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PV Modules

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Potential-induced degradation (PID) and its correlation with experience in the field

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ABSTRACT

Statistical data on potential-induced degradation (PID) testing at the panel level are discussed in terms of their field relevance and the actual occurrence of PID in the field, since the latter is strongly dependent on both the specific climate and the weather conditions at a certain location as well as on the system configuration realized in a specific power plant. The correlation of outdoor conditions and leakage current is also considered with regard to a suitable standard test for solar panels. Real outdoor data are shown for PID-affected power plants. Indoor and outdoor recovery is demonstrated for PID in real solar plants as well as in lab and outdoor set-ups. Apart from 'measuring' PID in suitable tests and in the field, approaches are also presented for the mitigation of PID at the panel and system level.

Introduction

Potential-induced degradation (PID) is a phenomenon which is still attracting increasing attention not only because of its growing importance for obvious technological reasons (higher system voltages and new technologies and materials), but also because of rising awareness throughout the whole PV community, beginning with the first publications on 'standard technology' more than two years ago [1–3]. This awareness is also due to the interest in energy yield optimization by minimizing overall degradation. PID is one degradation mechanism, and its occurrence in the field is not just dependent on the PID sensitivity of the solar panels and on a high potential relative to ground. Because of the variation of panel leakage current with temperature and humidity, a clear correlation can be observed between PID occurrence and weather conditions.

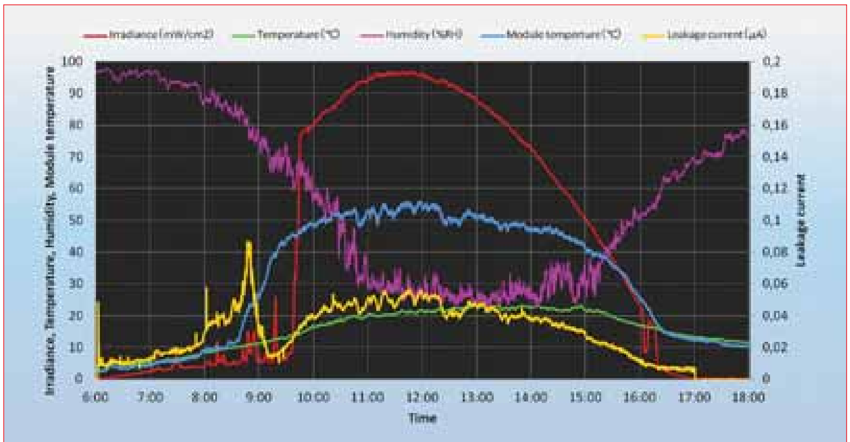

Figure 1. Leakage current data for a sunny day in the field (Yamanashi, Japan) for a panel at –1000V, depending on outdoor conditions (temperature, humidity and irradiance) [4].

Figure 2. Morning dew responsible for the leakage current peak in the morning [4].

"A clear correlation can be observed between PID occurrence and weather conditions."

Outdoor conditions and test methods

The occurrence and extent of PID strongly depend on outdoor conditions, as they determine the leakage current at the panel level. Fig. 1 shows the leakage current trend as a function of measured outdoor conditions for a sunny day. Two different regimes can be distinguished here: first, the leakage current peak in the morning, which is mainly humidity driven – morning dew as illustrated in Fig. 2; and second, a rather broad bump during the hours around noon, which is obviously mainly temperature driven because of the daily trend of irradiance.

As there are different and varying leakage currents observed not only in one location because of varying parameters, but also from location to location, it has to be stated that the risk of occurrence of PID in the field varies significantly for different

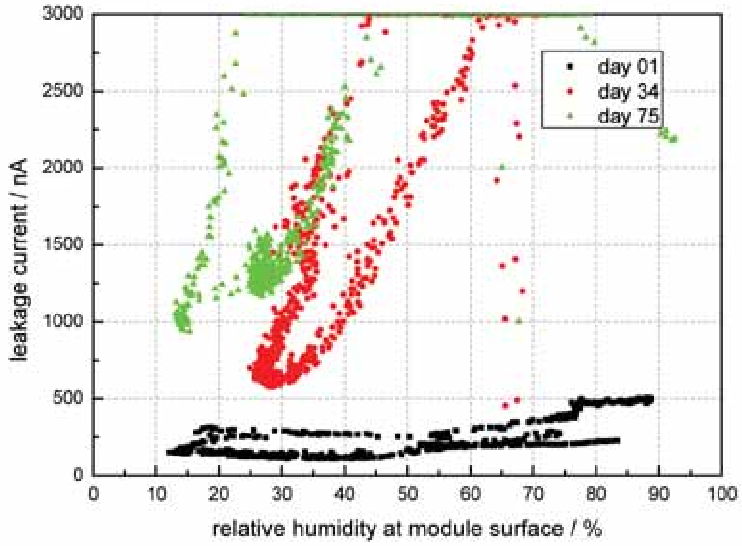

Figure 3. Leakage current data captured on three different days in the Canary Islands for two different panels at –1000V, as a function of relative humidity (RH) [5].

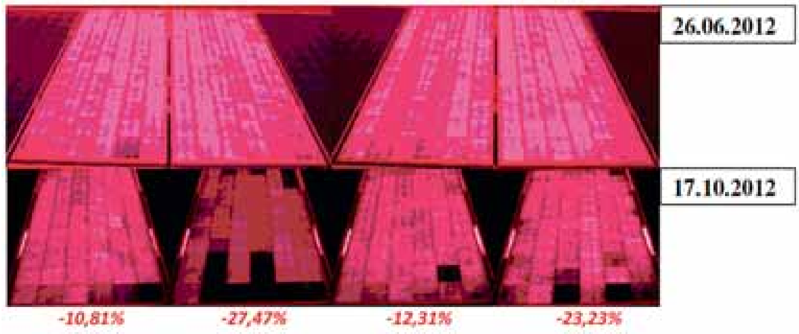

Figure 4. Progressive PID in the field: electroluminescence (EL) images and related power loss for a solar plant in southern Spain (about 30km from the sea).

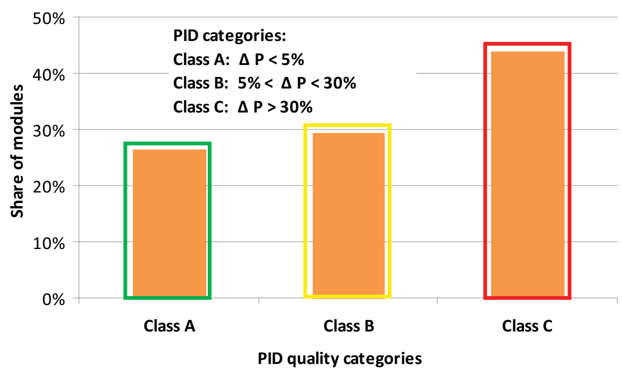

Figure 5. PID test results at PI-Berlin (2012: about 45 different panel types tested).

locations. Leakage current data from ISE Fraunhofer are shown in Fig. 3 for a location with a higher PID risk, the Canary Islands; leakage current data were captured for different panels on three different days. In the beginning, the leakage currents for the different panels were comparatively low, although the maximum values attained were about five times higher than for the lower risk region of Japan presented above (0.1μA vs. 0.5μA). Five weeks later there was a significant increase in detected leakage current, and after ten weeks the observed maximum leakage currents were about five times the initial values and partly beyond the detection limit of 3μA. This could somehow be correlated to an increase in surface conductivity as a result of salt particles and soiling.

These findings tie in quite nicely with the observation that a significant percentage of PID-affected solar plants are situated in rather warm climates and near the coast. Fig. 4 presents an example of a solar plant in southern Spain, where PID was detected after the hottest part of the year.

“A significant percentage of PID-affected solar plants are situated in rather warm climates and near the coast.”

With this in mind, the target of a suitable test method for PID and an upcoming standard test should be the simulation and the acceleration of real voltage-induced ageing and degradation in the field. There are an increasing number of test methods in place, but unfortunately they vary mainly in the specific test conditions for temperature, humidity and contact scheme. They all have one thing in common: they lack real outdoor correlation data. The most relevant test conditions are:

- Biased damp heat (DH): 60°C/85% RH, –1000V, 96h
- Biased DH: 85°C/85% RH, –1000V, 48h
- 25°C/50% RH,–1000V, Al-foil, 168h

The recent IEC draft 62804 Ed. 1.0 is based on the first of these parameter combinations. Although PI-Berlin employs all three of the different test conditions, most benchmarking data exist for the 85°C/85% RH condition (Fig. 5), leading to the conclusion that, in 2012, the majority of panels tested from different suppliers were still PID sensitive.

At the moment there are different ongoing activities aimed at round-robin testing for selected tests, comparing different test methods and correlating indoor and outdoor data, for example:

- PID round-robin testing based on IEC draft 62804 (system-voltage durability qualification test for crystalline silicon modules), coordinated by the National Renewable Energy Laboratory (NREL).
- PID round-robin project coordinated by PI-Berlin, focusing on the comparison of 60°C/85% RH/–1000V with 85°C/85% RH/–1000V and on the correlation of indoor testing and outdoor field degradation.

Impact parameter for PID – module and system design

When discussing PID with respect to risk mitigation by design, three different levels have to be distinguished:

1. Cell level
2. Panel level
3. System level / field

A PID-sensitive cell is a precondition for the observation of PID at the panel level. The cell level has already been presented by PI-Berlin in this journal [6], so the focus now will be on a discussion of the panel and system levels.

Panel level

When the solar cell specification allows for an accumulation of Na^+ ions within the SiN-ARC and a resulting interaction with the p-n junction (inverted emitter) [7], it is crucial whether or not panel design allows sufficiently high leakage current in order to support ion transport within the panel. Since the Na^+ ions from the glass are essential here, of the leakage current paths illustrated in Fig. 6 the one via the glass surface to the cell is the most important. This is supported by results from NREL, among others, which showed no evidence of the occurrence of PID in the case when Na^+ ions are absent from the front glass [8].

The general impact of the encapsulation material on the level of leakage current and therefore on PID has already been presented [1], showing that the electrical properties of the different material types play a key role. From recent measurements as shown in Fig. 7 it can be seen that bulk resistivity not only differs significantly for different material types, but also varies by about one order of magnitude between different EVA suppliers using different formulations.

The right choice of material combinations in production can therefore effectively suppress PID at the panel level by simply suppressing Na^+ ion transport to the cell. One option is to eliminate the Na^+ ion source in the first place, but probably an easier and less costly solution is to use high-resistivity encapsulation material.

System level

For PID to occur and be observed in solar installations a certain potential relative to ground must obviously exist. This potential depends not only on the system configuration but also on the specific panel position, as illustrated in Fig. 8. As a consequence, the power degradation in PID-sensitive panels depends on the type of grounding and the panel position within the panel string.

Because of the inverter concepts that are commonly used in solar plants, the most frequent configuration is the absence of a functional grounding of one of the poles, resulting in a so-called 'floating potential.' In Fig. 9 an example is given for the power loss due to PID as a function of the panel position for a panel string at a solar plant in southern Italy. As expected, the power loss increases with increasing (negative) potential relative to ground.

In order to identify and analyze in-field PID, power measurements alone are usually not sufficient and are often not practical as the only investigation method for large-scale solar plants. Infrared (IR) inspection (Fig. 10) and electroluminescence (EL) analysis (Fig. 11) have been proved to be suitable extensions

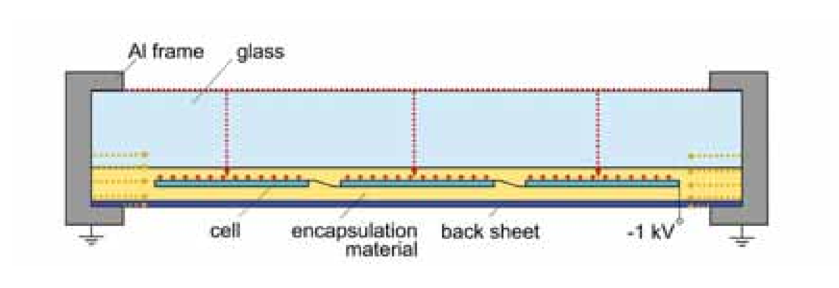

Figure 6. Leakage current paths in PV panels (adapted from Osterwald et al. [9]).

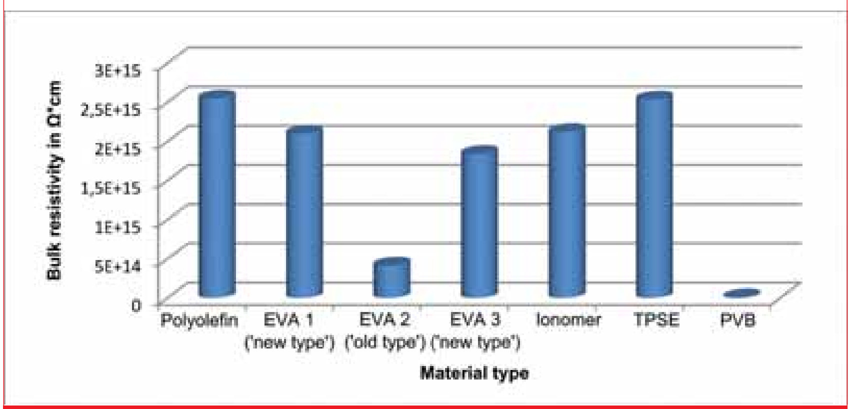

Figure 7. Comparison of bulk resistivity for different encapsulants.

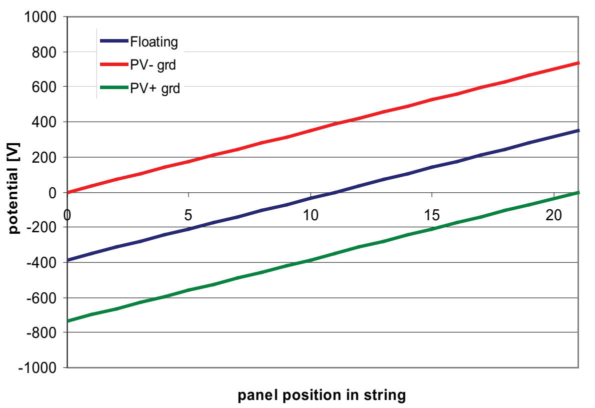

Figure 8. Potential relative to ground as a function of panel position and system configuration (functional grounding of either negative or positive poles, and no functional grounding or 'floating potential').

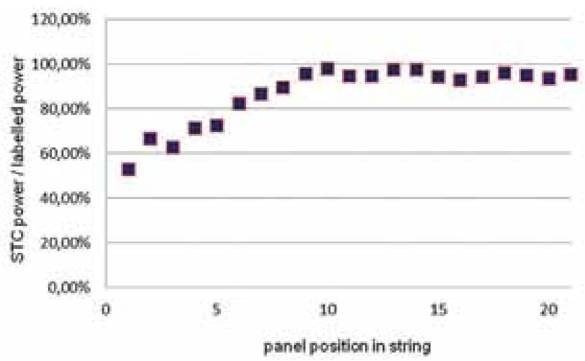

Figure 9. Power loss due to PID as a function of panel position (position 1 = closest to the negative pole).

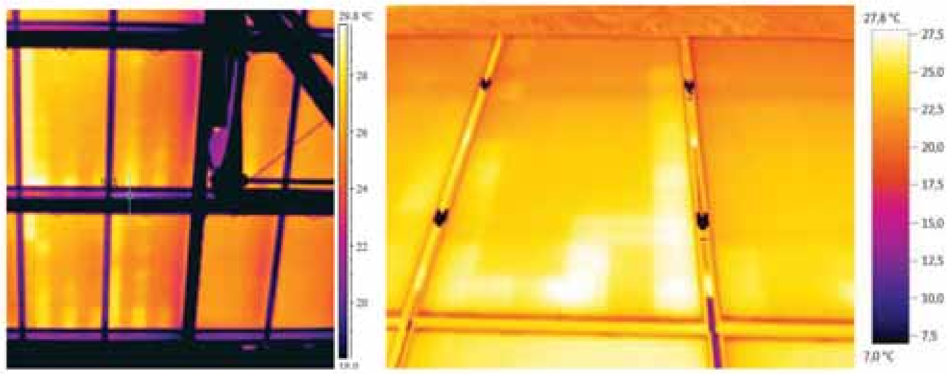

Figure 10. IR images of PID-affected panels in the field.

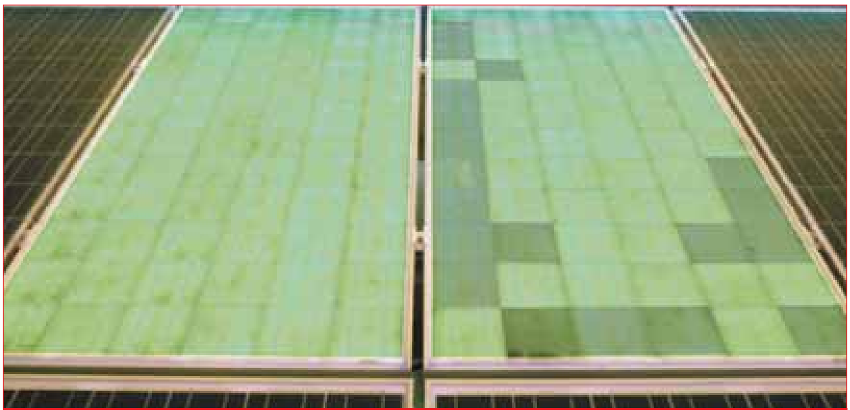

Figure 11. EL image of PID-affected panels in the field.

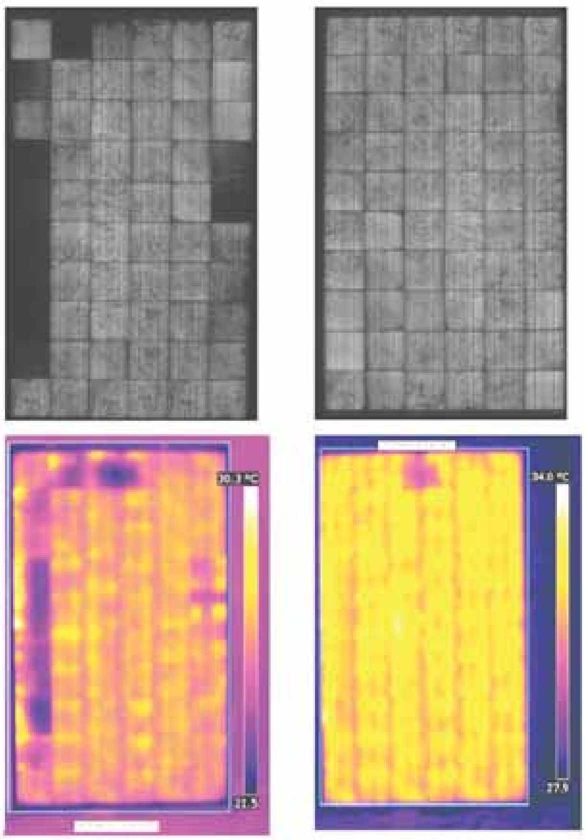

Figure 12. Complete recovery of PID field panels in a lab test: EL/IR images for PID field panels (left); EL/IR after recovery (right).

for PID investigations in the field. IR inspection in particular is useful for obtaining a (comparatively) quick estimate of the total number of PID-affected panels within a MW plant.

Recovery

As discussed earlier, PID is usually limited to the negative part of the string and can be avoided by a functional grounding of the negative pole. Owing to its principal reversibility it is also possible, under certain conditions, to recover from PID by 'removing' the negative potential, for example by reversing the potential or by functional grounding [1].

However, PID is not always completely reversible. Recovery time and extent depend not only on environmental factors but also on the degree of PID in the first place and therefore on the 'history' of the panel. Whether or not PID can be recovered from in the field by suitable measures has to be decided on the basis of recovery test results of PID-affected panels from a specific plant. For this purpose PI-Berlin is conducting both indoor and outdoor recovery tests for PID field panels.

> "Recovery time and extent depend not only on environmental factors but also on the degree of PID."

For an indoor test the maximum extent of recovery is determined under defined conditions, whereas for an outdoor installation it is determined under realistic environmental conditions. Fig. 12 shows PID field panels before and after recovery at 85°C/85% RH/−1000V.

In Fig. 13 the outdoor recovery results for different PID field panels, however, show a comparatively high recovery rate at the beginning, and a significant slowdown towards the end. In this example, recovery has not yet been completed, although there

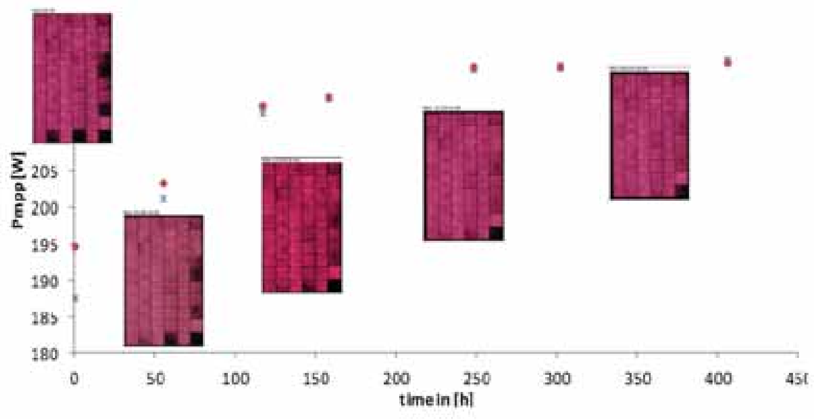

Figure 13. Performance under standard test conditions (STC) as a function of outdoor PID recovery time.

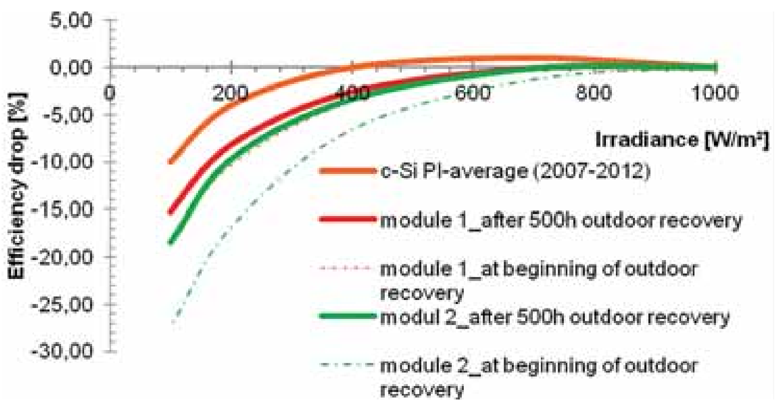

Figure 14. Recovery of weak-light performance of PID field panels compared with PI-Berlin average.

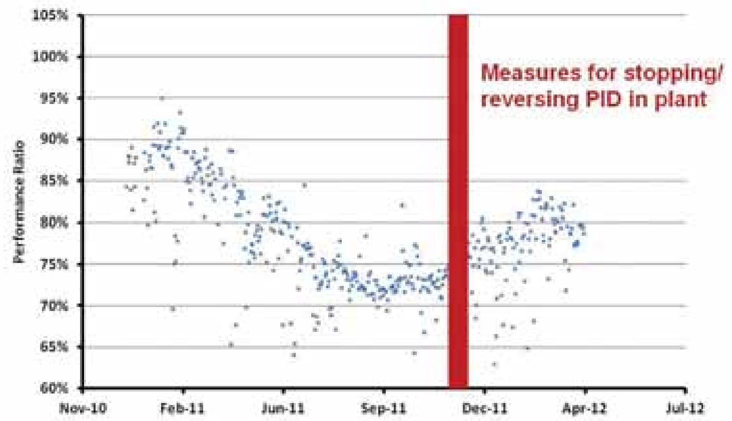

Figure 15. Performance ratio (PR) trend before and after PID measures were taken for the affected CT unit in the plant.

was no observed increase in power over a longer period of time (around three weeks).

Whereas the degradation had taken place within five months (until May 2012) in a solar plant in southern Italy, the recovery in an outdoor installation in Berlin at +400V for nine hours during the day was not yet fully completed after six weeks (August/September 2012) and power was still lacking.

Another aspect that should be mentioned with respect to recovery is the weak-light performance of PID field panels. With weak-light performance being even more affected in the first place than STC power, it should also be pointed out that, because the shunt resistivity usually remains at a lower level than previously, the weak-light performance tends to remain 'beyond' STC power recovery, as shown in Fig. 14 for two PID panels undergoing outdoor recovery.

PID in the field

In order to tackle PID in the field, PI-Berlin has developed a programme consisting of two parts:

1. An analysis of panels from the suspicious plant.
2. An in-field analysis and monitoring of measures taken.

In the first part, affected panels from the plant are investigated with respect to degradation and recovery behaviour. Once PID is confirmed in the lab, the second part focuses on the specific solar plant affected. Ideally, 'unusual' units or strings in the plant can be already identified by analyzing data from the plant-monitoring system, which can be accessed remotely. This is then followed by in-plant measurements, which – together with the results from part 1 – will lead to certain recommendations regarding suitable measures for the specific plant. The measures taken will then be monitored by repeated in-plant measurements.

> "PID on a large scale in a solar plant can significantly affect performance ratio."

PID on a large scale in a solar plant can significantly affect performance ratio (PR). Although this is only a very rough and nonspecific criterion for PID, from the point of view of investors and owners it is probably the most interesting one. In Fig. 15 the PR trend is shown for a PID-affected central transformer (CT) unit of a solar plant before and after suitable measures are taken.

After underperforming (CT) units have been identified in plant, measurements in plant are taken. Fig. 16(a) shows the results for a panel string in an East European plant. On the whole, the trend in power loss within a string due to PID was as expected: the closer to the negative pole of the string, the higher the power loss observed.

The trend within a panel string is not, however, always found to be 'ideal', as shown in the diagram for a string in a Spanish solar plant (Fig. 16(b)), where there are obviously additional superimposed factors (e.g. inhomogeneous panel batches, additional potentials). The corresponding EL and IR images for these panels are shown in Fig. 17. A power loss of up to 30% was detected in this plant for the majority of the panels measured in the negative part of the string (Fig. 18).

The main goals, however, when tackling PID in the plant are obviously not just to describe and analyze the situation, but also to achieve a measureable improvement in performance, as illustrated in Fig. 19.

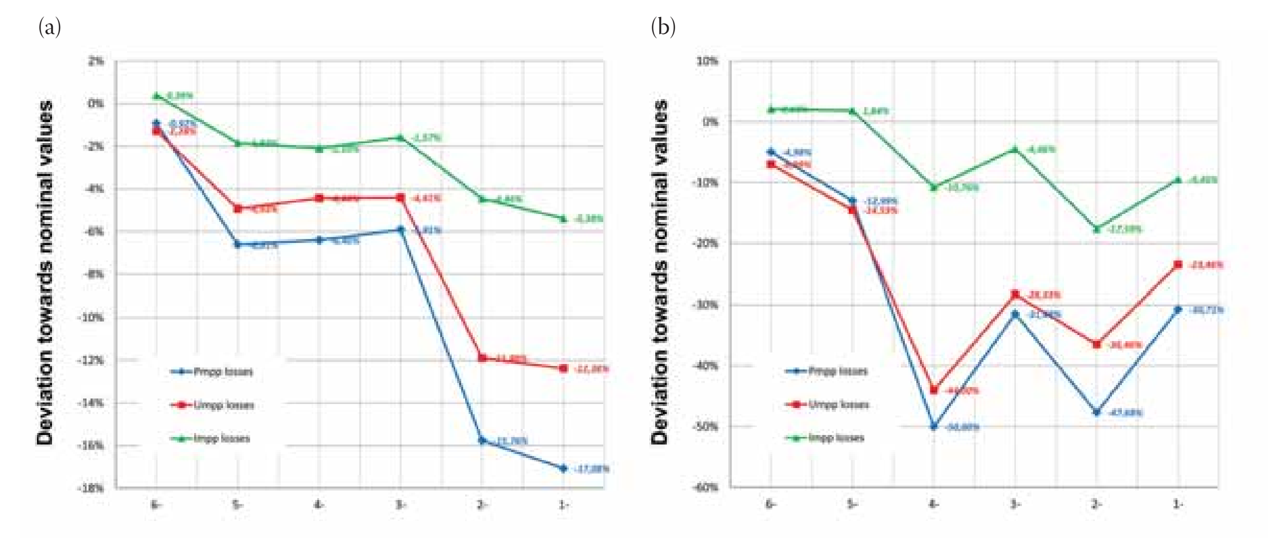

Figure 16. Power at the maximum power point (Pmpp) loss for panels in the negative part of the string depending on panel position ('–1' = closest to negative pole): (a) East European solar plant; (b) Spanish solar plant.

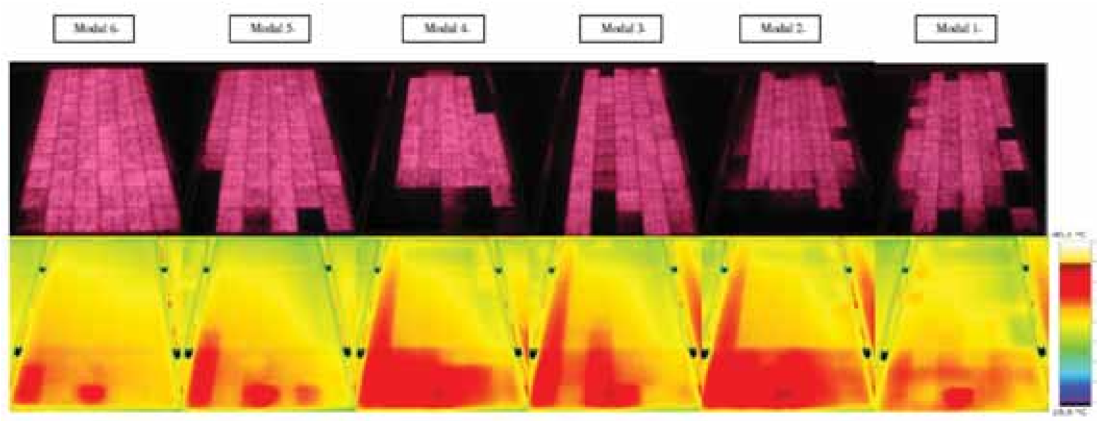

Figure 17. EI and IR images for panels in a PID-affected string in the Spanish plant.

"A standard lab test is urgently needed in order to have comparable data from different test labs."

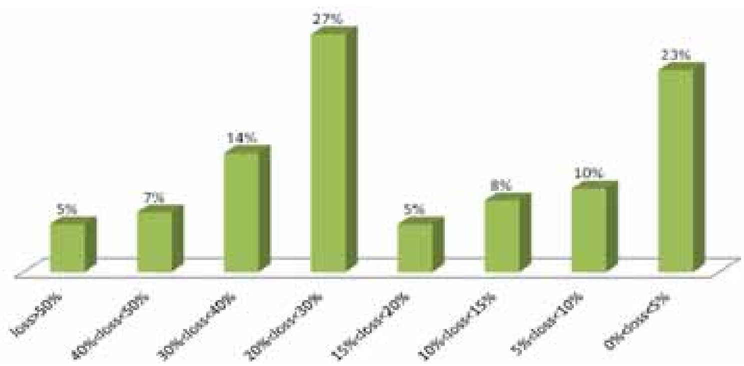

Figure 18. Distribution of the Pmpp loss for all the measured modules in the Spanish PID-affected plant.

Summary and conclusion

Although the majority of panels from different suppliers tested at PI-Berlin still show considerable PID in tests, it does not automatically mean that these panels will show significant PID once they are installed in the field. Additional factors, such as climate and weather conditions and the specific system configuration, play an important role in the occurrence of PID in the field.

Recovery from PID is possible by using suitable measures; however, the extent and rate of PID recovery in the field strongly depends on the outdoor conditions and on the degree of the initial PID. Weak-light performance of field panels is usually more affected than STC power, and the extent of recovery is often less.

Comprehensive measures for controlling PID have been taken by cell, encapsulation, panel and inverter suppliers, yet it is still not under control everywhere and is increasingly evident in the field. Accordingly, a standard lab test is urgently needed in order to have comparable data from different test labs.

Acknowledgement

The authors thank M. Köhl (Fraunhofer ISE) and S. Pingel (SOLON GmbH) for fruitful discussions and their cooperation.

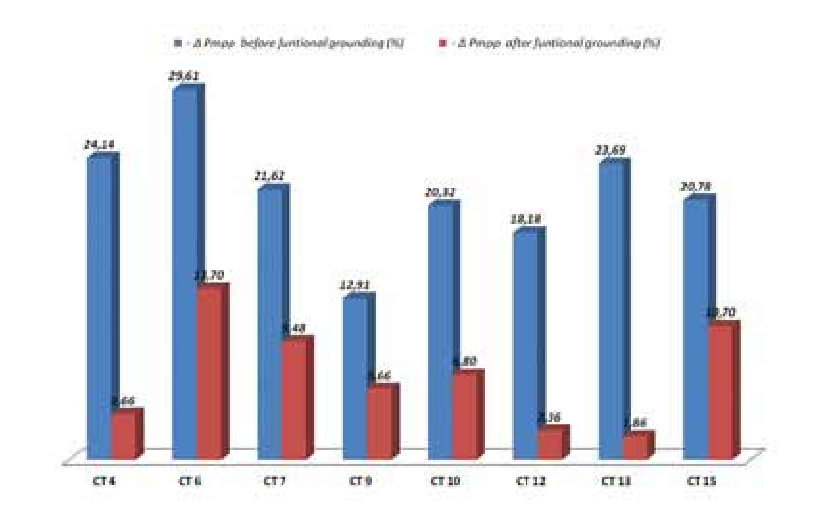

Figure 19. Trend for PID recovery (average values for panel power deviation for different CT units) in plant after functional grounding (time frame: May 2012 to Oct 2012).

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Power Generation

World PV capacity tops 100GW

The global cumulative capacity of solar PV passed the 100GW mark in 2012, according to analysis by the European Photovoltaic Industry Association. Figures published by the body reveal some 30GW of new capacity was connected in 2012, roughly equalling 2011, a record year for the global PV industry.

The global total now stands at 101GW. The fact global installations in 2012 did not increase substantially more than in 2011 reflects the problems faced by the industry last year with an over-supply of polysilicon and trade disputes between a number of the world's major trading blocs. The figures also show a shift towards a more global PV market, with 13GW of installations built outside of Europe compared to just under 8GW in 2011. In Europe the 23GW installed in 2011 fell to 17GW last year.

The top three European PV markets in 2012 were Germany (with 7.6GW), Italy (3.3GW) and France (1.2GW). The top three non-European markets were China (with at least 3.5GW and possibly as much as 4.5GW), the US (3.2GW) and Japan (2.5GW).

Global cumulative capacity of solar PV passed the 100GW mark in 2012.

European News Focus

AEG Power Solutions signs 240MW PV deal for Eastern Europe

AEG Power Solutions, a provider of renewable energy systems based in the Netherlands, has signed a contract with an unnamed Western European EPC company for 240MW of PV capacity in Eastern Europe.

Under the terms of the deal, AEG will provide complete electrical systems for installation at nine PV power plants in Eastern Europe which have a combined capacity of 240MW. These stations are composed of central inverters, transformers and medium voltage switchgear as well as monitoring and supervision systems (PV Guard) provided by AEG's subsidiary, skytron energy.

Upsolar targeting Serbia and Croatia via local partnership

Two potentially emerging European markets, Serbia and Croatia are proving important enough for 'fabless' PV module supplier, Upsolar, to team up with a regional partner, Plan-net Solar, to support the markets in 2013. The company said that Plan-net Solar was already installing a 40kW project featuring Upsolar modules in Serbia, one of the first players to enter this market. The companies claim that the Serbian and Croatian markets in 2013 could reach 10MW and 15MW of installations respectively, up from just 100kW and 8MW at the end of 2012.

Belgium's PV capacity surpassed 2.6GW in 2012

Belgium's cumulative installed PV capacity surpassed 2.6GW at the end of 2012, according to provisional statistics released by Belgian renewable energy association Apere. Apere said this means that at least 525MW of new PV capacity was added in Belgium in 2012 – although the association stressed this figure could eventually be revised upwards due to several additional PV projects that were completed in 2012 but are still undergoing examination.

The French-speaking region of Wallonia ended 2012 with more than 500MW of installed PV capacity, while the Flemish-speaking region of Flanders closed the year with 2,061MW. The region of Brussels registered an 83% annual growth rate.

Germany installs a record 7.6GW of PV capacity in 2012

Germany installed 7.6GW of PV capacity in 2012 beating its annual record set in the previous year which saw the country install 7.5GW, according to data from the German Federal Network Agency.

France doubles 2013 solar target to 1GW

The French government has released details of emergency measures to encourage US$2.6 billion worth of investment in the country's ailing solar industry.

Delphine Batho, French Minister of Ecology, Sustainable Development and Energy released details of emergency measures to encourage US$2.6 billion worth of investment in the country's solar industry.

The measures include doubling the previous target of 500MW of solar projects in France to 1GW, which the government believes would be achievable this year, by simplifying the tender process and introducing a domestic content allowance.

Cyprus' Ministry of Commerce green-lights 50MW of PV projects

The Cypriot Minister of Commerce, Industry and Tourism, Neoclis Sylikiotis, has announced the results of his department's call for tender for 50MW of PV capacity in Cyprus. Following the call for tender, Sylikiotis revealed that 121 investors had submitted 2,150 project proposals over four auctions. Only 23 solar projects were approved with a combined capacity of 50MW. The plants, which vary in size from 1MW to 10MW, will be built under the Cypriot government's renewable energy programme. When complete, these projects are estimated to generate around 80GWh of electricity every year.

Czech Republic passes 2GW milestone of solar installations

The Czech Republic has passed the milestone of over 2GW of cumulative PV installations in December. The latest figures from the Czech Energy Regulatory Office, suggest PV installations in November 2012 were 27MW and in December 2012 installations reached were 52MW, ending the year at a cumulative 2.085GW.

Greece reaches over 1GW of installed capacity in December 2012

Greek grid operator, Hellenic Transmission, has announced the country installed 1.126GW of solar PV capacity in December 2012, of which 298MW was rooftop capacity. Despite the ongoing economic and political turmoil in Greece, the country has experienced a 7% increase in installed PV capacity since November. Installations from 20kWp to 150kWp were the most popular in Greece with 76.670kWp installed in the Peloponnese, in December 2012.

Portuguese PV capacity close to 200MW

Cumulative installed PV capacity in Portugal hit 199MW at the end of November 2012, according to statistics published by the Portuguese Directorate General for Geology and Energy (DGGE). A breakdown of the statistics show that 5.8MW of PV capacity was installed in November. Including this figure, 41.3MW of PV capacity was installed in the country in the first 11 months of 2012.

Solar PV accounts for 1.7% electricity in Spain

Spain's National Energy Commission (CNE) has announced that electricity generated by solar PV accounted for 1.7% of the country's energy demand in December 2012.

The country added 163 PV systems in December, to a total of 59,603 installations that had access to the feed-in tariff last year, representing a total installed capacity of 4,475MW.

Americas News Focus

Californian third party-owned solar generated a record US$938 million in 2012

Third party-owned solar in California generated US$938 million in 2012, according to PV Solar Report, a research company specialising in solar market data, and residential solar firm Sunrun.

The companies claim that this record figure for 2012 – which went directly into local businesses and communities – means that Californian third party-owned solar generated approximately the same amount in 12 months as in the previous five years

Source: Stion

Third party-owned solar in California generated US$938 million in 2012.

in total. It also represents 74% of the state's residential solar market.

European investors planning 100MW PV project in São Paulo

A group of unnamed European investors have presented plans to develop a 100MW PV plant in the Brazilian state of São Paulo.

According to the Department of Energy, the group of investors plan to collaborate with Brazilian partners from the private as well as public sector to develop the 100MW facility.

DuPont heads downstream to aid US-based residential solar installer

DuPont Photovoltaic Solutions is supporting US PV installer Astrum Solar on product specifications for modules that improve efficiency and system lifetimes, ultimately lowering costs and increasing investment returns.

Source: DuPont

DuPont will be advising Astrum Solar on specifications for materials used in the fabrication of PV modules.

DuPont said that it would be advising the installer on specifications for materials used in the fabrication of PV modules, notably its own such as 'Tedlar' polyvinyl fluoride film-based backsheets.

Pacific Solar submits plans for 123.5MW of Chilean solar plants

Pacific Solar, a Chilean PV project developer, has submitted plans for the development of two PV plants with a combined capacity of 123.5MW to the Chilean environmental authority Servicio de Evaluación Ambiental (SEA). Both plants will be constructed in the Antofagasta region in northern Chile, near the town of Maria Elena, in the province of Tocopilla.

Isofotón signs MoU for 150MW PV project in Mexico

Spanish PV developer Isofotón has inked a memorandum of understanding (MoU) with the Yucatán state government in Mexico to develop a 150MW PV facility in the country.

The MoU was signed on 8 February by Ángel Luis Serrano, Isofotón's President and the Governor of Yucatán, Rolando Zapata Bello, and the Environment and Economy Secretaries of the State of Yucatán.

Construction of the US$360 million project is due to begin on January 1, 2014 and will be constructed in six phases, each of which will involve the installation 25MW of PV capacity. The project is expected to take two years to complete and become operational.

Bosch Solar Energy and aleo solar secure US$100 million in financing for select US projects

Bosch Solar Energy North America and aleo solar have secured and made available US$100 million to fund select commercial and residential solar projects within the US. The funding is available immediately through the aleo Power Network and the Bosch Solar Energy PowerPro network. Through this programme, the companies will provide financing for 100% of project costs for approved commercial projects sized at 50kW or more, as well as for residential projects valued at US$50,000 or less.

First Solar acquires 50MW New Mexico plant

Thin-film manufacturer First Solar has announced the acquisition of the 50MW Macho Springs Solar project from developer Element Power in Luna County.

The project is expected to be completed in 2014, providing up to 400 construction jobs, and producing enough clean, renewable energy to power over 18,000 homes while displacing 40,000 tons of CO_2 per year – the equivalent of taking 8,000 cars off the road.

Source: First Solar

First Solar has increased its project portfolio with its latest acquisition.

Utility firm El Paso Electric (EPE) signed the power purchase agreement in November last year. Terms of the transaction were not disclosed.

Virgin seeks proposals for renewable energy project on Sir Richard Branson's Necker Island

The Carbon War Room (CWR), Homer Energy and Reznick Think Energy have

Source: Jeff Foust

Virgin Limited Edition will provide renewable energy to Richard Branson's Necker Island.

News

launched a request for proposals (RFP) on behalf of Virgin Limited Edition to provide renewable energy and energy services on Necker Island in the British Virgin Islands.

The companies will receive bids to provide engineering and design services for a 750kW PV system in an open field, an 8kW PV system on the island's Great House as well as solar carports.

The successful implementation of renewable energy systems on the island will represent the "centrepiece" of the 10 Island Challenge programme launched by entrepreneur Sir Richard Branson and the CWR at the Rio+20 United Nations Conference on Sustainable Development in June 2012. The programme seeks to assist 10 island nations around the world to reduce their dependence on fossil fuels by 2020.

Asia & Oceania News Focus

China increases solar target by 67% – yet again

For the fourth time in two years China has increased its solar energy target from 21GW by 2015 to 35GW. In the last ten years, China's solar PV cumulative installed capacity has already grown by 67 times the average annual growth.

Franco-Indian cooperation brings floating solar to Eastern India

EPC company Ciel et Terre has developed the Hydrelio system which, the company says, saves valuable land by converting water area into a solar power plant ranging from 1 to 50MW in size. Klystron Electronics, facilitated by the European Business and Technology Centre (EBTC), has signed a Memorandum of Understanding with Ciel et Terre to implement the Hydrelio system in Eastern India.

Other water-related solar initiatives in India include PV projects alongside ponds. The government of the state of Bihar, in the northeast of the country, has announced it will develop up to 150MW of solar PV next door to ponds.

Phono Solar and Symbior Energy plan 40MW PV project in Thailand

Chinese solar manufacturer Phono Solar and Symbior Energy, a Hong Kong-based renewable energy company, have signed a strategic cooperation to jointly develop a 40MW solar project in Thailand. Under the terms of the agreement, both companies will jointly develop, fund and construct the PV facility. The project will be implemented in several phases, each of which will involve developing 8MW of PV capacity. Phono Solar is keen to grow its presence in key emerging markets including South America.

Government of Kazakhstan targets 1,040MW of renewable energy by 2020

The government of Kazakhstan has set a target to generate 1,040MW of renewable energy by 2020. The government has revealed that it will reach this target by developing four solar plants, 13 wind power plants and 14 hydropower plants. Although no further details were unveiled by the government, media reports suggest the solar plants would have a total capacity of 77MW.

Saibu Gas plans two PV plants in Fukuoka, Japan

Saibu Gas, a Japanese gas provider, has announced plans to construct two PV facilities in Fukuoka Prefecture, Japan, with a combined capacity of 3.2MW.

The first plant will have a capacity of 1.5MW and will be built on approximately 14,800 square metres of unused land on the property of the company's Nagasaki factory. It will be equipped with PV modules supplied by Solar Frontier which will help to generate around 106 million kWh of electricity every year.

The second plant will be built on approximately 22,300 square metres of land owned by Asahi Glass in Wakamatsu-ku, a ward of the town of Kitakyushu. It will require and investment of US$4.9 million. The facility will have a capacity of 1.7MW and be equipped with around 6,900 PV modules provided by Sharp Corporation. When complete it will generate around 164 million kWh of electricity annually.

Vikram Solar commissions 40MW PV plant in Rajasthan

Module manufacturer Vikram Solar has commissioned a 40MW PV facility in Rajasthan, India. A spokesperson from Vikram Solar confirmed that the plant became operational in the first quarter of 2013. As EPC provider, Vikram Solar began constructing the plant in September 2012. In addition to providing EPC services, the company also supplied and installed its polycrystalline modules at the plant. The 40MW project – which required an investment of around US$74 million – was awarded to Vikram Solar under the Indian government's Jawaharlal Nehru National Solar Mission.

Africa & the Middle East News Focus

Ethiopia celebrates its first solar panel

Project developer SKY Energy International and Metals Engineering Corporation (METEC) are celebrating the fabrication of the first solar panel in Ethiopia.

The country's first turnkey module assembly line was commissioned in April 2012 in a partnership between Spire Corporation, SKY and METEC. The installation of the factory was successfully completed in December 2012 at which time engineers laminated, tested and produced the solar panels.

Powerway wins contract for 94.5MW South African project

Powerway South Africa, the South African subsidiary of Chinese solar mounting solutions provider Powerway, has been awarded a contract to provide turnkey services for a 94.5MW PV project in De Aar, South Africa.

Under the terms of the contract, Powerway South Africa will supply and install its solar mounting systems and provide turnkey services for the project.

Phoenix Solar completes Saudi Arabia's largest PV system

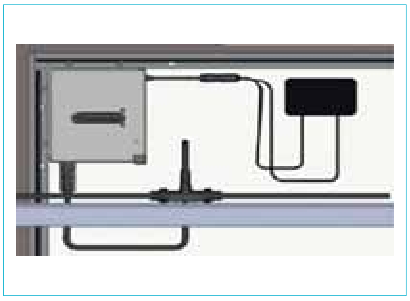
Phoenix Solar, an international PV project developer, has completed what it claims to be the largest PV system in Saudi Arabia.

The 3.5MW PV system has been installed on the grounds of the King Abdullah Petroleum Studies and Research Center located in Riyadh, helping the energy research centre to achieve a Leadership in Energy and Environmental Design platinum certification – an internationally recognised sustainable building standard.

Owned by Saudi Arabian oil company, Saudi Aramco, the ground-mounted system was designed and constructed by Phoenix Solar. It is equipped with 12,684 PV modules supplied by Suntech and covers an area of 55,000 square metres. The grid connected system will supply an estimated 5,800MWh of electricity every year.

Product Reviews

Canadian Solar



Canadian Solar offers high-performance AC module for faster ROI

Product Outline: Canadian Solar has launched its next generation 'ResidentialAC' system less than six months after the initial launch. The upgraded system combines the 250W PV module with its next generation microinverter while maintaining a standard 25-year system performance warranty.

Problem: Until now, PV system installers had to make use of first-generation micro inverter technology. The company claims installers, homeowners and investors will benefit from fewer repairs, safety advantages of not working on high-voltage DC electricity, and faster installations with lower labour and material costs.

Solution: The ResidentialAC system comes with a 25-year microinverter reliability warranty to match its module warranty by eliminating the key life-limiting components in the current first generation of AC microinverters. The company said that the system is available in a 250W power rating format, up from 215W when launched last year, and that the microinverter can be used with higher power class modules up to 300W and operates in high temperature environments above 65ºC.

Applications: Available in a sleek black frame, the module is designed specifically for home and business solar installations.

Platform: Canadian Solar's ResidentialAC system also includes monitoring software, allowing customers module-level tracking of solar panel performance to optimize the system's solar energy production.

Availability: January 2013 onwards.

SMA Solar Technology

SMA's 'Cluster Controller' can monitor 75 string inverters

Product Outline: SMA Solar Technology has launched its new SMA 'Cluster Controller,' which is designed to support the monitoring and control of decentralized PV power plants in connection with its string inverters up to the megawatt range.

Problem: The larger the PV plant, the more that undiscovered faults or yield issues even on a small level can quickly become a major financial issue for plant owners. Accurate and comprehensive monitoring of plants has become an essential part of operations, which can reduce costs and improve yield.

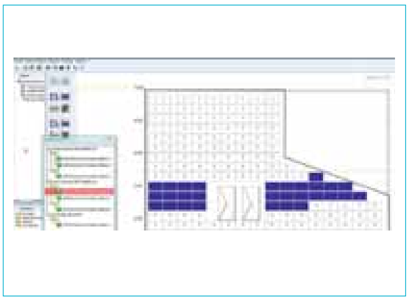
Solution: The SMA Cluster Controller is claimed to offer reliable monitoring and control of up to 75 string inverters thanks to the ethernet-based Speedwire fieldbus and use of a dual-core microprocessor. The 100Mbit/s bus system provides plant operators with optimum data transmission rates for plant monitoring and fast processing of measured values, status updates and plant control commands. Different connection options for the sensors enable plant operators to evaluate nominal plant power more precisely, according to the company. In addition to the status updates, the nominal plant power can be viewed using SMA's Sunny Portal.

Applications: Decentralized PV power plants

Platform: The flexible modular system solution can incorporate any number of Cluster Controllers. The Speedwire fieldbus and the PV farm management system using the Power Plant Controller provides for the possibility to flexibly change the power output of PV plants. The modular system can be expanded as needed because additional clusters can be added conveniently.

Availability: January 2013 onwards.

Vela Solaris



'Polysun 6' PV planner upgraded for battery employed self-consumption analysis

Product Outline: Vela Solaris has introduced 'Polysun 6' PV planner software that includes new features to ease the daily work of solar system planners as well as being enhanced to provide simulation analysis of battery storage requirements for self-consumption.

Problem: Both residential and commercial-scale rooftop PV systems are becoming increasingly complex to plan because of the need to fully maximize energy output as well as cater for the growing need to include analysis requirements dictated by battery storage systems.

Solution: In addition to yield predictions and inverter set-up, the new version of Polysun 6 is claimed to provide the optimal PV module layout on the roof surface. Developed by Vela Solaris in close cooperation with SolarGeo3D, this new feature allows the user to place PV modules both automatically and manually. In a typical operational sequence, after the roof shape has been determined, modules are placed so as to optimally cover the available roof surface either completely or with the given number of modules. For inverter set-up, string allocation is thus calculated and displayed. Module placement and string allocation can be easily edited manually at any time, with the intention of providing an optimized roof plan and obtaining accurate yield predictions.

Applications: Commercial and residential roof planning of PV systems.

Platform: Polysun 6 is now equipped with a new calculation model for rechargeable batteries: the battery is charged when the amount of power produced exceeds that used. The solar energy generated on the roof can then be used at a later time.

Availability: February 2013 onwards.

Product Reviews

IMO

IMO offers off-the-shelf controller designed for axis PV systems

Product Outline: The IMO Solar Cube has been developed by IMO Precision Controls as an easy-to-set-up solar-tracking and measurement controller with the flexibility to adapt to either one- or two-axis PV module installations to track the sun's movement.

Problem: Improving yield from ground-mounted PV systems has become increasingly important with lower FiT rates or under a PPA. Solar tracking can provide increased yield but still has be competitive technology with fixed ground-mounted systems.

Solution: The sun's position is calculated using local time and date and comparing this with the longitude and latitude location of the solar array. The Solar Cube calculates the 'zenith angle' and the 'azimuth angle', which together exactly specify the position of the sun in the sky to within 0.01 degrees. To position the array the Solar Cube uses feedback from an electronic compass device connected via RS232 or RS485, which then activates the solar array's actuators until the correct position is reached. The compass is mounted directly on the array frame to give accurate positioning information.

Applications: One- or two-axis solar panel installations.

Platform: The Solar Cube can be configured to control up to four arrays from one controller, providing additional savings.

Availability: Currently available.

Amphenol Industrial

Amphenol and Tigo optimize junction box technology for integrated applications

Product Outline: Amphenol Industrial Global Operations, a global leader in interconnect systems, has incorporated Tigo Energy's PV optimizer technology into a new junction box, increasing power efficiency and eliminating the need for add-on products. The HBFMMJ-ES50, also known as the Tigo-Amphenol Optimizer, is the first in its class to receive CSA certification for integrated smart module technology.

Problem: Installers and system owners want the highest ROI by increasing energy production and maximum system uptime for new systems and retrofits.

Solution: Amphenol's new junction box incorporates Tigo Energy's optimizer directly onto the solar panel module, fulfilling the growing demand for lower part count and easier installation of solar products. The integrated technology also increases energy harvest and system uptime, while providing better arc, fire and safety hazard mitigation. The optimizer maximizes the power output of each solar panel module. It also delivers module level data for operational management and performance monitoring as well as providing the ability to deactivate a high-voltage DC bus for safe installation, maintenance and firefighting.

Applications: Used for residential, commercial and utility-scale photovoltaic applications.

Platform: The new junction box is certified to CSA-C22.2 No. 107.1-01 for general-use power supplies, and features 300W of maximum power, 52V of DC output and a maximum current input of 10A.

Availability: February 2013 onwards.

Trina Solar

Trina Solar to offer its first dual-rated frameless module for harsh conditions

Product Outline: Trina Solar is planning to introduce the 60-cell PDG5, the first in a new line of dual-rated frameless modules. The PDG5 is said to be resistant to potential-induced degradation (PID) and micro-cracking and does not require grounding. The PDG5 is optimized for reliable performance under stressful environmental conditions.

Problem: Although glass/glass modules are believed to offer higher levels of robustness, especially in harsh environments, they have typically suffered from higher cost and carry a weight penalty.

Solution: The PDG5 features front and back layers of special heat-strengthened glass replacing the traditional backsheet materials of conventional solar modules. The PDG5 provides a heavy-duty solution for environments of high temperature and humidity, conditions that can accelerate performance degradation. The resulting module has increased resistance to micro-cracking, PID, module warping, and degradation from UV rays, sand, alkali, acids and salt mist.

Applications: Commercial rooftop and utility-scale applications in all major markets.

Platform: By reducing the module's glass thickness from the industry standard of 3.2mm to 2.5mm, and applying an anti-reflective coating to the front glass, transmission is enhanced by an estimated 2.5%. MC4PLUS photovoltaic connectors increase system reliability. Additionally, the modules are designed for higher 1000V IEC and 1000V UL applications.

Availability: Worldwide shipments expected in the second half of 2013.

Modelling for PV plant optimization

Joshua S. Stein & **Bruce H. King**, Sandia National Laboratories, Albuquerque, New Mexico, USA

ABSTRACT
Because most of the costs of developing a PV power plant are paid before any energy is generated, optimizing the energy production from the plant is critical during plant design. Lost energy and increased operations costs due to non-optimal site characterization, technology choice, plant design, installation and other factors result in lower energy production and a higher levelized cost of energy (LCOE). Many design decisions are based on results from PV performance models. Current PV performance models can represent only some of the differences between sites, technologies, designs and operations choices. This paper provides a description of what is currently known about some of the performance tradeoffs faced by PV plant designers and operators. It presents a vision for improving PV performance models so that in the near future a full optimization can be carried out to improve the performance and lower the costs of PV plants. This will hasten the adoption of clean energy production from the sun.

Introduction

While the cost of PV components and systems are rapidly falling, the upfront costs of PV (before any energy is generated) are still high. This is especially true when compared with conventional, fossil-fuel-based generation, where capital costs are lower but a significant portion of the total cost is for fuel over the lifespan of the plant. In contrast, with PV systems the fuel is 'free' and the costs are associated with initial installation and operations and maintenance. As a result, there is a high incentive to accurately predict and optimize the performance of the PV plant. This paper focuses on the issues that need to be considered in order to ensure that a PV plant will perform to its maximum potential. This is a relatively new field and there are plenty of opportunities for improvements.

The levelized cost of energy (LCOE) ($/kWh) is a useful measure to optimize because it factors in all aspects of a project's value, including costs and revenue as well as the time value of money. A simple representation of the LCOE is

$$\mathrm{LCOE} = \frac{\sum_{n=1}^{N} \frac{C_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \quad (1)$$

where the numerator represents the total cost (C) in today's currency of the system over its lifetime (N years), and the denominator is the total amount of energy produced (Q), which is corrected for degradation and discounted for time. Future costs and revenue from energy production are discounted each year (n) by the discount rate (d) (or weighted average cost of capital), which takes into account the time value of money and the perceived risk of the project. A more detailed description and discussion of the LCOE can be found elsewhere [1].

> "To optimize PV system performance and the LCOE, it is necessary to evaluate and compare costs and benefits related to technology and design decisions."

If the value of the energy is higher than the LCOE, the project will earn a profit over its lifetime. The LCOE can increase if operating costs are higher than expected and/or if energy production is less than predicted. Optimizing (minimizing) the LCOE is complicated by the fact that costs and energy production are correlated in ways that are just beginning to be understood. For example, careful monitoring of the health of a PV system may increase system output by reducing downtime when components fail. However, this will only lower the LCOE if the additional cost of monitoring is less than the revenue gained from greater energy production as a result of higher availability. Conversely, simply lowering the cost of the system by using less-expensive components will not reduce the LCOE if the lower quality components compromise reliability and increase operations and maintenance costs during the life of the system. In order to optimize PV system performance and the LCOE, it is necessary to evaluate and compare costs and benefits related to technology and design decisions.

PV plant design considerations

Proper design is critical for building and operating a top-performing PV plant. At each step of the process, choices must be made that will have a significant impact on the performance (both expected and real) of the plant. In many cases, the choice that must be made may be whether or not to perform a certain type of pre-assessment, rather than being purely engineering or technology based. The following steps in the development of a PV plant will be explored:

- Site characterization
- Technology choices
- Array configuration
- Electrical system configuration

An example comparison will then be given of three PV systems, each using a different design and/or module technology. This comparison highlights some important balance-of-system (BOS) implications of common design tradeoffs. This is followed by a discussion of plant operations issues and, finally, a discussion of opportunities for improving PV performance models to support performance optimization studies.

Site characterization

Assessment of the local solar resource potential is an important aspect of the selection of a PV site: inadequate prior assessment is a common source of underperformance. Long-term, high-quality irradiance datasets are available at only a handful of locations. Satellite data can be processed to estimate irradiance in most locations, but even this data can be biased by several per cent [2]. PV developers frequently set up a dedicated weather station at a site for a few months to a year and then compare direct measurements with other historical datasets, including satellite estimates. Developers often assume that bias errors can be identified and reduced as a result of the comparison (e.g. see Thuman et al. [3]).

The quality of the irradiance data for such a field campaign is critical: use of inaccurate sensors, failure to clean and maintain sensors, or lack of sensor calibration can introduce significant errors in irradiance measurements. It is also important to realize that certain irradiance sensors only respond to a specific spectral range, which may not match the absorption spectrum of the planned PV modules. For example, the use of a silicon photodiode pyranometer to characterize the irradiance resource for a CdTe PV system may introduce a bias error.

> "The quality of the irradiance data for a field campaign is critical."

The proximity of the nearest available, long-term irradiance dataset to the selected site is important to consider as well, since annual insolation can vary significantly over even short distances (microclimates). Gueymard and Wilcox [4] presented a study of irradiance variability in space and time for the USA, using a 0.1° (~10km × 10km) gridded dataset; they concluded that spatial variability was highest (covariance of annual average insolation >5%) along the coastlines and mountainous areas, and lowest in flat areas. Local studies in San Francisco have shown an even larger spatial variation in annual insolation across the city (>12%) [5]. For sites lacking such detailed studies, interviewing local residents, real estate agents, farmers and so on can be quite effective in identifying if there are local patterns in insolation.

Finally, uncertainty in irradiance and insolation data can be significant and should be considered. Uncertainty in irradiance (e.g. see Myers [6]) is different from the uncertainty in annual insolation, especially when the uncertainty that matters most is the mean annual insolation over the lifespan of the PV plant. Random errors that affect irradiance measurements will average out over time and have little effect on annual insolation. However, bias errors in the irradiance measurement – which can result from sun angle, temperature and spectral effects – can compound and result in a bias error in annual insolation.

Interannual variability of insolation is important to quantify because it largely determines the variation in energy production (and revenue) from year to year. Interannual variability quantifies the possible differences in insolation from year to year caused by climate cycles (e.g. ENSO/El Niño/La Niña, etc.). Gueymard and Wilcox [4] also examined interannual variability across the USA and found direct normal irradiance (DNI) to be 2–3 times more variable than global horizontal irradiance (GHI). They also found that interannual variability appears to be positively correlated with cloudiness, with lower variability in sunnier locations. They found that the variation in the annual insolation was typically (95% of the time) less than 2% in the best PV locations in the southwest USA. In contrast, in more diffuse climates, such as central New York State, the interannual variability was much higher (>10%). Thus it might be expected that the annual PV output from a PV plant in a diffuse climate would vary year to year more than in a sunny climate.

Figure 1. Two-axis tracker used at Sandia National Laboratories in Albuquerque, New Mexico, to measure module performance parameters.

Figure 2. Analysis of *I-V* curves under a variety of conditions is used to estimate PV module performance parameters for a number of available models.

Technology choices

PV developers are faced with a plethora of technology choices when designing a system. Understanding the differences between the available technologies is critical to optimizing system performance. Most developers today choose module technology by weighting differences in module performance, quality, reliability, cost and confidence in the manufacturer's ability to honour its warranty.

Module performance characteristics have a large effect on design considerations. Higher efficiency modules require less area and fewer BOS components (racks, wires, combiners, etc.), and may run cooler than less efficient modules. Differences in module design and materials can affect operating temperature and resulting efficiency. These aspects should be considered when comparing module costs. In addition, the spectral response of different cell types (c-Si, CdTe, CIGS, etc.) to actual site conditions can result in a spectral shift (actual performance relative to performance at the G173 spectrum). Nelson et al. [7] have shown that CdTe performance is sensitive to the spectral changes due to the variation of precipitable water in the atmosphere, which fluctuates seasonally at many sites. Available PV performance modelling applications do not include calculations that take account of this effect and may therefore introduce a seasonal bias error when estimating performance for CdTe systems.


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Figure 3. Long-term PV system test bed at Sandia National Laboratories, Albuquerque, New Mexico. Module and inverter performance is continuously monitored, and components are re-characterized annually.

Another factor that can be important is the degree of consistency between modules. Differences in module performance characteristics can lead to mismatch and reduced performance when connected in series and operated at a single voltage typically controlled by the inverter. Module warranties usually include a tolerance on the power rating (e.g. 215W±5%, which means a module delivers between 204 and 226W at STC). At Sandia National Laboratories in Albuquerque, New Mexico, outdoor performance is characterized by accurately measuring *I-V* curves from modules mounted on a two-axis tracker (Fig. 1).

These data are used to determine the parameters for PV performance models (Fig. 2), including the Sandia Photovoltaic Array Performance Model [8]. PV systems for long-term performance tests are also fielded at a number of different climate locations to measure system performance degradation rates, identify failure modes and track differences in performance in different weather conditions. Fig. 3 shows one of these long-term test beds at Sandia.

Array configuration

Optimizing an array configuration involves choosing between fixed tilt and tracking, which has implications for row-to-row spacing, ground coverage area and total site area. Module orientation on racks can also affect performance, especially when row-to-row shading is an issue. Single-axis tracking can boost annual energy production by as much as 25% and dual-axis tracking by as much as 45% compared with a fixed-tilt system, but increased land is required to see these gains [9]. Additionally, tracking includes a mechanical system, which needs periodic maintenance and repair. Modern tracking controllers provide 'back tracking', which minimizes row-to-row shading at the beginning and end of the day. Such systems can require more stringent site preparation to ensure that the rows are level, since differences in row-to-row elevation can introduce row-to-row shading during certain times of the year. Some single-axis trackers add a tilt to the rotation axis (e.g. Sun Power's T20); this design results in a 6–7% increase in the plane-of-array irradiance (compared with horizontal-axis tracking) and is less sensitive to levelling issues, reducing the amount of site preparation that needs to be done [10]. However, tilted-axis tracking requires more land area than horizontal configurations because of the need to space the arrays further apart to minimize row-to-row shading.

Electrical system configuration

The electrical configuration of a PV array affects the system performance in a number of ways. Current electrical codes in the USA (NEC) limit the maximum DC voltage to less than 600V. However, increasing the DC voltage can improve performance for several reasons. At higher voltages, currents are lower, resulting in smaller resistive losses in the DC wiring and/or enabling the use of wire with less copper and thus lower in cost. Higher voltage systems can utilize strings with more modules, reducing the number of combiner boxes and the wiring between strings. To explore these benefits, utility systems in the USA (which are not constrained by NEC) are installing systems designed for 1000V. Some systems in Europe are experimenting with voltages as high as 1500V. However, using higher system voltages also has its drawbacks, such as potential-induced degradation (PID) of certain types of module in humid environments [11,12]. Research into the costs and benefits of increasing DC voltages for PV systems is ongoing.

Designing for optimum performance requires that the electrical configuration take account of any shade that will be cast on the array. Module orientation (portrait vs. landscape) and string wiring design can be very important if any shading will occur. A small band of shade along the short edge of a typical PV module affects string performance far less than a shade band hitting the long edge, because the typical wiring pattern and the use of bypass diodes between the substrings of PV cells inside a module mean that shade along the short edge affects each substring equally and results in less mismatch between substrings. Similarly, shade affecting one string that is connected in parallel with other stings will have a different effect than the same shade area affecting parts of each of the parallel strings [13].

"Designing for optimum performance requires that the electrical configuration take account of any shade that will be cast on the array."

New inverters and power electronic devices, including DC–DC converters, are making the electrical design of PV systems more complicated, but also offer additional avenues for optimizing system performance. Centralized inverters are usually able to convert DC to AC more efficiently, but, as arrays grow larger, DC current must be harvested from greater distances, resulting in longer wire lengths and greater DC losses. Switching to smaller 'string' inverters can reduce these wiring losses. In addition, because power output reporting is usually included as part of the inverter, smaller inverters may increase the fidelity of the monitoring system, providing granular information about power production from smaller parts of the system and allowing outages to be identified and located earlier. Such advantages must be weighed against differences in efficiency and costs.

BOS implications of technology choice

Sandia National Laboratories recently conducted a design study of three typical 2MW PV systems to illustrate and document design, cost and performance differences between different PV technologies [14]. The study focused on three system types:

- **System A**: mc-Si modules (230W STC); fixed latitude tilt
- **System B**: CdTe modules (75W STC); fixed latitude tilt
- **System C**: mc-Si modules (230W STC); horizontal single-axis tracking

A solar developer was commissioned to provide the system designs, with each system using eight 250kW inverters. Systems A and C were designed with the same modules and shared the same string configurations. Annual system performance was then estimated for a location in Salt Lake City, Utah, using PVSyst [15]. LCOE was estimated using the System Advisor Model [16]. The following summarizes some of the design differences between these systems.

System B required 3.1 times the number of modules and 1.4 times the land area needed by System A. The open-circuit voltage for System B's CdTe modules was 2.4 times greater than for the mc-Si modules used in Systems A and C, resulting in fewer modules per string.

	System A	System B	System C
Technology	mc-Si fixed	CdTe fixed	mc-Si tracked
Installed cost estimate [$/Wp]	2.88	2.99	3.24
Plane-of-array irradiance [kW/m^2-yr]	1980	1980	2340
Annual output [MWh/yr]	3295	3407	3784
Levelized cost of energy [¢/kWh]			
IPP financing	11.71	11.76	11.98
Cash financing	8.0	7.7	7.9

Table 1. Energy production and cost estimates for three example 2MW PV systems in Salt Lake City, Utah.

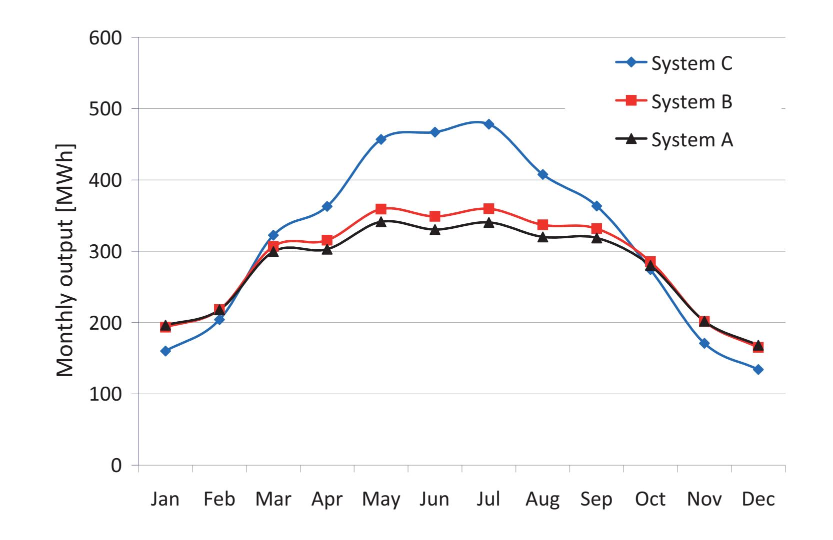

Figure 4. Estimated monthly system output (from Quiroz and Cameron [14]).

This, combined with the greater number of modules, resulted in System B requiring 8.6 times the number of strings needed for the mc-Si system. Because of the larger number of strings, System B required 1680 combiners and 48 recombiners, while Systems A and C only needed 48 combiners and no recombiners. System B also required more wire and trenching work than the other systems.

Total installed costs, predicted annual performance and LCOE are summarized in Table 1. Because of the larger area and greater number of components to install, System B had higher installation costs. However, despite significant differences between these system designs, the LCOE values are very similar.

The real performance differences show up when the predicted output for the systems is compared over time: Fig. 4 shows predicted monthly system output. Note that System C produced significantly more energy during the summer but only slightly less energy during the winter than Systems A and B. This is a general characteristic of most horizontal single-axis tracked systems.

Fig. 5 shows the average hourly output for each month and demonstrates that System C can deliver more energy at the beginning and end of the day during the summer because of the tracking of the modules; during the winter, however, the output in the middle of the day is significantly lower than the fixed-tilt systems. The CdTe system (System B) shows slightly improved performance during the summer owing to the lower temperature coefficient on the maximum power of CdTe modules compared with mc-Si. These plots illustrate that different designs can significantly affect the timing and magnitude of power generation, which in turn can affect how these systems impact the electrical systems to which they have to be connected.

Operations

After an optimized PV plant has been designed and built and then connected to the grid, there is no guarantee that it will perform as predicted. Large PV plants comprise hundreds of thousands, sometimes millions, of components. The system is exposed to the environment, which can include dirt, plants, animals, snow, hail, wind and rain. Catastrophic losses (e.g. glass breakage due to hail) are usually covered by an insurance policy, but other issues such as cleaning the array,

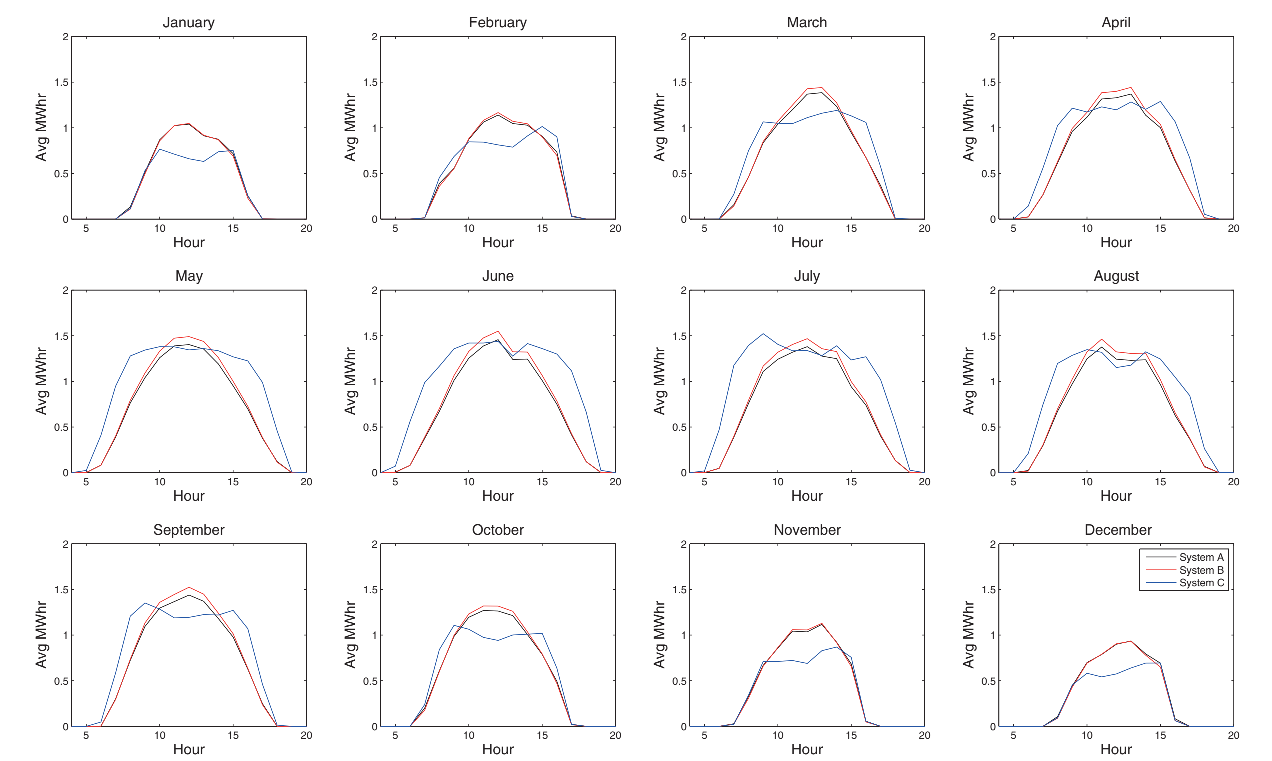

Figure 5. Estimated average hourly output by month for systems in Salt Lake City, Utah (from Quiroz and Cameron [14]).

grass/brush cutting around the array, and damage caused by vegetation control equipment, by wind or rain, or by animals are usually the responsibility of the owner/operator or covered in an operations and maintenance (O&M) contract.

Soiling on the array is one of the most significant causes of lower than expected energy production [17,18]. Since there are no standards for measuring soiling rates as part of site characterization activities, each developer uses its own methods (e.g. see García et al. [19] and Caron and Littmann [20]). Seasonal variations can be significant, requiring a minimum of a one-year study to adequately characterize a site. Soiling rates are also highly dependent on module tilt angle [21–23]. For much of the world, commercial rooftop systems with modules oriented at a typical 10–20° tilt may be more dramatically affected than utility-scale plants where the modules are mounted at latitude tilt. There is evidence that certain soil constituents may affect PV performance far more than the absolute amount of soil on the module surface, thus complicating measurement techniques [24,25]. Cleaning modules is expensive and may even be impractical or impossible because of water availability or environmental regulations. The soiling level is dependent upon rainfall frequency and intensity, so an assessment of precipitation patterns and forecasts can help to optimize cleaning schedules. Research into soil-resistant coatings for module surfaces also offers promise for reducing energy loss from soiling [26].

Accelerated soiling studies are a new field with promise to reduce the time required to determine the severity of loss due to specific soil types and morphology, as well as assisting in determining appropriate mitigation methods [27,28].

Large PV arrays are frequently located in dry regions. However, covering these areas with impervious modules can cause precipitation to be focused on the lower edge of the array, creating a microenvironment favourable to rapid growth of vegetation. This can lead to an increase in the frequency of vegetation management when compared with the estimates made before the PV plant was built.

"Existing PV performance modelling applications are designed to estimate annual energy yields and can only distinguish between a few differences in designs."

Finally, in the event of module breakage or excessive degradation, it is important to realize that spare parts matching the original components may not be available after installation, since technology changes rapidly. The inclusion of spares in the initial design may be important to keep the system running at full capacity. Without spares, performance can suffer beyond a simple reduction in nameplate capacity, and strings must be reconfigured to remove failed modules.

Modelling expected performance

Evaluating the sensitivity of choosing between different sites, technologies, designs and operations strategies requires a sophisticated set of models and data. Existing PV performance modelling applications [29] are designed to estimate annual energy yields and can only distinguish between a few differences in designs (e.g. fixed vs. tracking, some module technology characteristics, etc.), and are not able to evaluate others (e.g. interannual and spatial variability, spectral and electrical mismatch, distributed vs. centralized power conversion, reliability of components, O&M strategies, etc.). These other factors are frequently included in the evaluation, but with simplified assumptions or derating factors. Users rarely have a robust technical basis for estimating the magnitudes of these factors and therefore model estimates are considered to have large uncertainty bounds. Some modelling applications do offer valuable features that allow uncertain parameters to be sampled from distributions, with the aim of minimizing or maximizing a reported output. An example of this feature is included as part of the National Renewable Energy Laboratory's System Advisor Model (SAM), which incorporates 'sensitivity' and 'optimization' functionality [16].

To respond to this situation, Sandia National Laboratories and the US Department of Energy have recently started the PV Performance Modeling Collaborative (PVPMC) [30] to collect and organize the latest information about PV performance modelling algorithms and methods, as well as to provide open-source analytic tools and functions that can be used to validate and expand existing modelling algorithms and methods. On the PVPMC website [31], stakeholders can research various modelling algorithms, download documents and gain access to a PV modelling toolbox for Matlab called the PV_LIB Toolbox. This toolbox contains numerous documented open-source functions; it offers a great resource for model developers and users for learning about and validating the modelling steps used for estimating PV system yields.

The PVPMC has organized the process of PV performance modelling into a set of standard steps (Fig. 6):

1. **Irradiance and weather**. This step involves choosing a source for defining the irradiance and weather conditions expected for the site. Common sources include typical meteorological years (TMY), satellite-derived data and on-site ground measurements. There are numerous possible approaches for choosing weather inputs for performance modelling studies.
2. **Incident irradiance**. This step aims to translate irradiance measured at standard orientations (horizontal, plane of array and normal to the sun) to beam and diffuse components on the plane of the array. Many algorithms are available for performing these translations but there is little consensus on which one is the most accurate for any given site and system.
3. **Shading, soiling and reflection losses**. If the array is partially shaded or the modules are soiled, the amount of the incident irradiance available for conversion to electrical energy is reduced. There are various algorithms for calculating the shading and its effect on the system, but only a few methods exist for predicting the amount of soiling on the array with time. Usually this step is treated with a constant or time-varying derating factor.
4. **Cell temperature**. The PV cell temperature is influenced by a number of factors, including module materials and construction, mounting and racking configurations, and the incident irradiance (modified by shading and soiling), wind speed and ambient temperature, among other variables. Many methods have been proposed for estimating cell temperature from these variables.
5. **Module *I-V* output**. In this step the *I-V* curve of the module is predicted under the conditions described previously: irradiance (including spectrum) and cell temperature. There are various types of model that have been applied (single diode, semi-empirical, etc.).
6. **DC and mismatch losses**. This step involves estimating the losses in the DC circuit(s) due to wire resistance

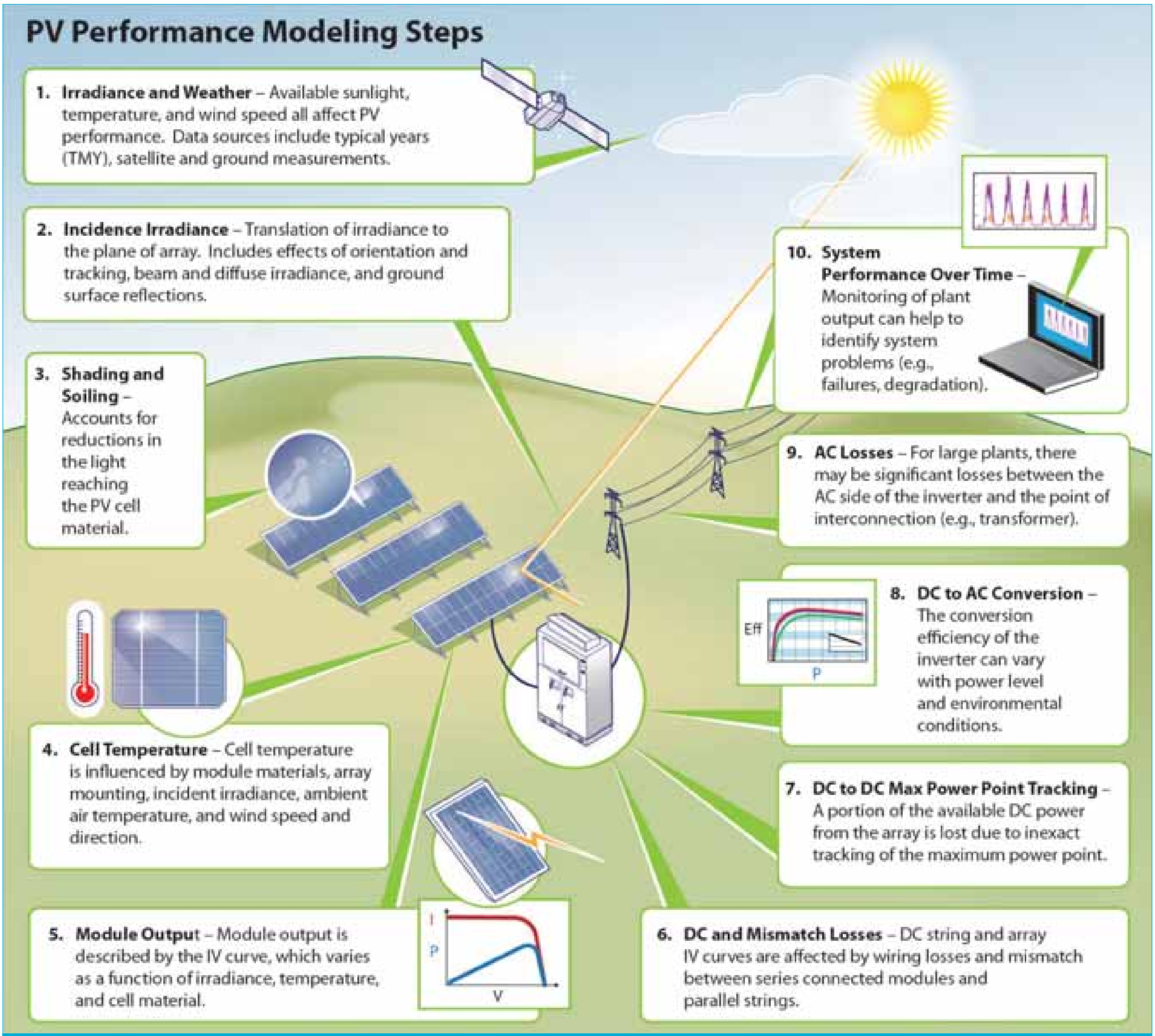

Figure 6. Standard steps in modelling PV plant performance (from the PV Performance Modeling Collaborative [31]).

and mismatch between series-connected modules and parallel strings. Few performance modelling applications include this step explicitly, except by means of a scalar derating factor. Treating this part of the performance modelling problem is especially important in order for PV performance models to accurately represent performance of distributed-array technologies designed to reduce such mismatch losses (DC–DC converters, string-level inverters, microinverters, etc.).

7. **DC to DC maximum power point tracking**. Most, if not all, modelling applications assume that the array's DC voltage can be held at the maximum power point (MPP) for the array at all times. Differences between maximum power point tracking (MPPT) algorithms mean that the ability of different inverters to hold the MPP varies. Furthermore, PV systems may sometimes operate away from the maximum power point by design (e.g. 'curtailment' or operation at non-unity power factor).
8. **DC to AC conversion**. This step accounts for the conversion efficiency of the inverter. This efficiency can vary with environmental parameters such as temperature and with electrical conditions such as DC power level.
9. **AC losses**. Once the power has been converted to AC it must be transmitted to a point of interconnection (revenue meter). Any losses along this transmission path (wire losses, transformer losses, etc.) are represented in this step. Few existing models represent this process in any detail [32].
10. **System performance over time**. Monitoring of plant output can help to identify system problems (e.g. degradation and component failures). There are a number of metrics used to track and evaluate system performance (performance ratio, performance index, etc.).

In many cases, existing PV performance models skip one or more of these steps by making assumptions or by including a loss or derating factor. As PV system design options become ever more complicated with new components (e.g. DC–DC converters), many of these previously overlooked and simplified steps will see more attention.

"Work on standardizing the modelling process has begun as part of the PV Performance Modeling Collaborative."

Power Generation

Conclusions

The wide variety of PV system technologies, system designs, site conditions and operations strategies means that complex models of PV system performance are needed in order to represent the performance of PV plants. Existing performance models only include a subset of the features and processes that affect system performance, and differences between these models mean that direct comparisons are difficult to make. The result is a lack of consensus on which model to use and how to document performance analyses so that the PV community has confidence in the performance predictions. Work on standardizing the modelling process has begun as part of the PV Performance Modeling Collaborative and provides a framework for adding model improvements, developing best practices and allowing different models to be compared in a consistent way. As PV performance models improve, the promise of full system optimization will eventually be fulfilled.

Acknowledgement

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The next big step – Optimizing the performance of PV power assets

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ABSTRACT

To achieve project cash flow expectations, it is necessary to operate, maintain and optimize the performance of a PV power asset to meet or exceed the pro forma operating assumptions. To assume as given the achievement of these model assumptions is both naive and risky. Experience in operating the largest fleet of solar PV power plants in the world has demonstrated that project financial hurdle rates can be missed by as much as 25% if the plant is not well maintained and its performance is not optimized. Conversely, an optimized PV asset can generate cash flows 2–10% higher than expected if the optimization approach described in this paper is implemented.

Why PV performance optimization is needed and why now

New technologies typically follow a four-phase maturation cycle as they are being commercially deployed: 1) technology breakthrough, 2) market development, 3) technology build-out, and 4) maintenance and service. This last phase in the deployment of a new technology, the actual servicing of the technology, is the least glamorous of the phases and is often taken for granted by asset owners and investors. Specific operating assumptions, such as plant availability and component degradation rate, are part of every financial model used to finance an asset purchase. But how does the investor know those assumptions are valid and if the projected returns will be realized on their particular project?

What is optimization?

To optimize the operating performance of any system, PV or otherwise, the first order of business is to understand what the term 'optimization' really means. At its most basic level, optimization is the process of finding the 'best available' solution for a system, given a set of operating variables with an accompanying set of constraints. To optimize a system or project, it is first necessary to characterize how it works within a set of physical and commercial limits and the operational degrees of freedom that the owner has to work with.

> "Optimization is the process of finding the 'best available' solution for a system, given a set of operating variables with an accompanying set of constraints."

The ABC of optimization

A simple way to think about optimization is what has been called the 'ABC' of optimization (Fig. 1). The letter 'A' prompts the question 'What can be **A**djusted?'; 'B', 'What is the **B**est solution?'; and 'C', 'What are the **C**onstraints?' Each of these components of optimization will be addressed.

Before considering how system variables can be adjusted and how they are constrained, however, it is important to understand what is meant by the 'best', or optimal, system solution. Typically, when considering what the best solution to a problem is (also called the 'objective function'), the maximum or minimum result from a set of options is the object of the search.

What can be adjusted?

Controllable parameters, or 'decision variables', are those operational and commercial 'knobs' the operator can adjust to obtain different operating results from the PV power plant. Though PV plants have fewer controllable parameters than other generation technologies, such as fossil and wind plants, there are still more operating degrees of freedom than many owners recognize. For example, most inverter original equipment manufacturers (OEMs) will allow operators to 'over-drive' the inverter beyond its nameplate rating if staying within the limits of the warranty.

Why is this important to know? Many PV power plants are built with excess DC capacity, meaning that the DC arrays can deliver, under ideal conditions, more power than the nameplate rating of the inverters. This extra DC power is often 'wasted' at the inverter because of a factory setting that 'clips' the power so as not to exceed the AC nameplate rating of the machine.

Why waste that power and not realize the potential revenue? Some power purchase agreements (PPAs) and interconnection agreements (IAs) limit plant power to the total inverter AC nameplate capacity of the project, while others allow generation 5–10% above guaranteed capacity. If the project limits generation to the inverter nameplate capacity, it may be possible to negotiate an amendment to PPAs or IAs and obtain written approval from the inverter OEM to increase the factory power limit by several

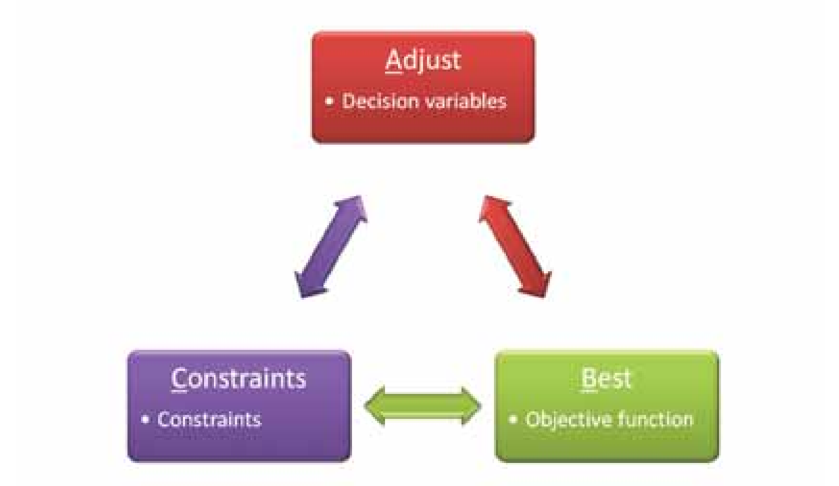

Figure 1. The ABC of optimization.

percentage points. This one modification alone can increase revenues for some projects by 2–10% per year.

What is the best solution?

For a financial asset, such as a PV power plant, the problem to be solved is usually not how to maximize revenues or minimize expenses, but how to maximize revenues while minimizing expenses. In other words, what solution returns the highest profit for the project? This is because, although the goal of maximizing revenues sounds like a good objective, a short-term perspective on maximizing revenue could actually result in suboptimal profits for the project in the long term. For example, the plant operator could 'over-drive' the inverters or increase panel-washing frequencies to achieve maximum project revenues while simultaneously adding cost at a higher rate, resulting in reduced project profits. Maximizing project revenues in isolation is therefore typically not what is best for the project.

> "The problem to be solved is usually not how to maximize revenues or minimize expenses, but how to maximize revenues while minimizing expenses."

Similarly, minimizing project expenses is usually not the right goal either. Taken to an extreme, a good way of minimizing project expenses is to do no maintenance. Is this practice advocated? Certainly not! It is known intrinsically that neglecting a power generation asset, even a fairly low maintenance asset such as a PV power plant, does not result in maximizing long-term project returns. Indeed, inspections have revealed that many rooftop PV power systems which have been neglected or poorly maintained are operating at only 80–90% of their system capability.

The reason why maximization of long-term project profitability is the right goal for a PV power project is that it seeks to find the balance between generating high revenues and making the right investment in the reliability and maintenance of the system.

What are the constraints?

Constraints are the limits imposed on the project's controllable parameters. Think of the optimization problem for the project as a multidimensional box where the constraints are the walls of the box and the controllable parameters are the 'room' in which one has to manoeuvre within the box. A particular corner in one of those rooms in the box is the optimal solution for which project profitability is maximized (Fig. 2).

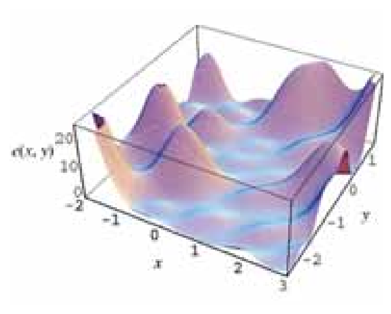

Figure 2. A multidimensional optimization problem.

PV power plant constraints come in three types: 1) physical, imposed by the plant equipment; 2) commercial, imposed by the operating agreements and warranties; and 3) regulatory, imposed by local and national rules and regulations.

Physical constraints are the limits of the plant hardware. For example, a 320W panel can generate 320W of power under standard test conditions (STC), but there is nothing that can be done to make it generate more than 320W of power. More panels can be added to increase the plant's DC capacity, or a fixed-tilt system can be converted to a tracking system to increase the plant's capacity factor, but the panels are still only generating 320W of power.

Commercial constraints are those non-physical limits imposed by the equipment manufacturers and operating agreements. For example, though an inverter may be able to generate 5–10% more AC power than its nameplate rating, if the OEM warranty would be violated by over-driving the inverter, the operator is commercially constrained not to do so. Similarly, if the project interconnection agreement dictates that the plant can never deliver more than 25MW at the point of interconnection, the plant will not deliver more than 25MW of instantaneous power, even if it has additional AC capacity available to do so on a sunny day.

Regulatory constraints are constraints imposed by operating permits. For example, some PV projects in the desert of the southwestern USA prohibit owners from using water to clean the plant's PV modules. Unless a non-water method of reducing soiling is available to the operator, the plant's performance degradation rate is at the mercy of local environmental and rainfall conditions.

The balance and benefits of optimization

The benefit of optimizing the operational performance of a PV power asset is, of course, the ability to improve project cash flows. The balance in optimizing the profits of the project is to ensure that the best solution for a given set of operating variables and constraints is what is *really* being determined. This is typically not a trivial solution and requires that commercial and technical analysts properly characterize the system and its controllable parameters and constraints. For the most complex analysis, the problem can be modelled using a 'solver' software tool to find the best solution from among thousands or even hundreds of thousands of candidates. To accommodate a large data set, a robust 'data historian' – such as OSIsoft's PI System – can be particularly useful when analyzing historical and real-time plant data.

> "The benefit of optimizing the operational performance of a PV power asset is the ability to improve project cash flows."

Exceeding project operating performance

For the asset to exceed its projected operating performance, it is necessary to evaluate which of the pro forma operating assumptions have some available margin, and how sensitive revenue and expense are to changes in those parameters. The first step is to develop a simple table showing which project variables can be adjusted and what the projected profit impact might be (Table 1).

For example, though an owner may be able to generate an additional 2–5% of production from their facility, there is almost always a cost in doing so. The operator could over-drive the inverters to generate additional peak capacity during some hours of the year; however, what impact would increasing the inverter's operating duty have on reducing the equipment's life and increasing its maintenance costs? Similarly, an operator could increase the module-wash frequency of the facility and improve the overall electrical conversion efficiency of the modules, but at what cost? To properly determine the 'right number' of module washes for a given PV power facility,

Variable	Potential improvement [%]	Profit impact [%]
Production	2 to 5	–5 to +5
Efficiency	1 to 10	–10 to +8
Availability	1 to 2	–10 to +1
Corrective maintenance labour	10 to 50	–5 to +5

Table 1. Adjustment of project variables.

the owner needs to characterize the past, present and future recoverable degradation rate of the modules and the unit cost of cleaning.

Finding the right balance

The above example of finding the optimal module wash frequency for a facility demonstrates why a robust physical and financial model needs to be developed in order to find the optimal solution for each plant operating scenario. Until the relationship between recoverable power, time-of-delivery power rates, module-cleaning effectiveness, historical and projected degradation rates, and cost of module washing is modelled, the optimal solution to the problem cannot be properly determined. Optimization solver technology determines the best answer by setting up a mathematical model of the problem and exercising every option until the best (most profitable) solution is found.

If the resources for utilizing a solver for each scenario to be evaluated are not available, the next best approach is to model the problem using a spreadsheet and then perform a simple sensitivity analysis on the variables that most impact the optimal solution. Once this model has been established, each assumption is varied within a range of reasonable values and the change in profit recorded during this process. It should be possible to quickly identify which variables most influence project profitability.

Figure 3. Soiled solar panels – the case for module-wash optimization.

For the module-wash frequency problem, module soiling rate (recoverable degradation) and power price are likely to be the variables with the highest sensitivity. The best available information for soiling rate, power price, wash cost and other key variables is inputted to the spreadsheet, and the module-wash frequency variable is then adjusted. It will soon be discovered that, as the module-wash frequency is varied from one to two to three washes per year (and so on), the law of diminishing returns kicks in and profits peak, and then drop quickly. The module-wash frequency that returns the best profit strikes the balance between too many and too few washes.

PV power optimization options

As mentioned above, though PV power systems do not have as many controllable parameters as traditional fossil-fuel power plants, there are still quite a few to consider. Some of these are listed in Table 2.

Category	Optimization variable	Comments
Production	Inverter over-drive	Increasing this increases peak capacity but can also increase major maintenance expense. Interconnection agreement may not allow guaranteed capacity to be exceeded.
	Inverter start-up/shutdown control	Adjust inverter control logic to wake up earlier and generate more morning/afternoon energy.
	Under-performing combiners, strings and modules	Repair of these will increase production capacity but may increase O&M labour costs if not performed using automated fault detection software.
	Tracker control under diffuse irradiance conditions	Adjust tracker control algorithms to not directly track the sun under high diffuse irradiance conditions.
	Tracker wakeup/sleep control	Improve early morning and late afternoon tracking algorithm to capture more energy.
Efficiency	Module-cleaning frequency	Recovered power must exceed cost of recovery.
	Inverter-container cooling	Improvement can reduce the high ambient temperature de-rating of the inverter but may have CAPEX and OPEX impacts.
Availability	On-site spare parts or critical spares	Model the component failure rates, availability (production) impacts, parts availability and parts cost.
	On-site staff or pay for contractor response/availability guarantees	Model the current and projected forced outage and de-rating rates and incremental labour/guarantee costs.
	Component failure rates and tracker operation	Estimate the cost/benefit of adding automated fault-detection/ network operations centre (NOC) services.
O&M costs	Corrective maintenance costs	Estimate the reduction in truck roll costs by having real-time component fault codes visible from a NOC and the part available prior to dispatching the service provider.

Table 2. Controllable parameters of PV power systems.

Time to choose

After all the viable decision variables for optimizing performance have been listed for a facility, the economic impact has been estimated, and the commercial and technical constraints have been evaluated, it is then time to begin developing a detailed model and to 'down-select' from the list of options. Some of the performance optimization options will be eliminated, as they are deemed too risky or would require re-permitting the plant or re-negotiating a power purchase agreement. Others will generate return rates and payback periods that easily meet project hurdle rates. All appropriate stakeholders and specialists should be involved in the decision-making process, and it must be ensured that equipment or system warranties are not violated. Prior to implementing the optimization project, quality baseline performance data need to be gathered so that the incremental economic benefit of the project can be measured once it is in place.

Summary

The PV power marketplace has matured and is now approaching 100GW of generation capacity worldwide. To confirm PV as a mainstream electricity-generation asset class, it is time to demonstrate to project stakeholders and to the public and private sector that this is a generation technology to take seriously for decades to come. Optimization of the technical performance of the asset is the next step in making solar mainstream and an attractive investment option.

> "Optimization of the technical performance of the asset is the next step in making solar mainstream and an attractive investment option."

PV power systems need to meet and exceed their pro forma economic returns. Performance optimization methods and systems common in the traditional power and wind industries should now be deployed to realize rates of return 2–10% greater than originally modelled during project financing.

About the Author

Steve Hanawalt is a founding partner of Power Factors, LLC – a company set up in 2012 to provide PV performance optimization services. He has worked in the independent power industry since its birth in the early 1980s, and has spoken around the world on the topic of optimizing PV power project returns. Steve received his Bachelor of Science degree in mechanical engineering from the University of California, Berkeley, in 1982, with a specialization in energy conversion.

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Market Watch

News

EU tariffs against Chinese could cost European solar industry €27.8 billion

The imposition of European Commission tariffs of up to 60% against Chinese manufacturers could lead to 242,000 job losses in Europe during the first year, new research claims.

At the end of last year, the European Commission launched anti-dumping and anti-subsidy proceedings against Chinese wafer, cell and module manufacturers, following complaints from EU ProSun, a group of European manufacturers led by German manufacturer SolarWorld.

Prognos's report shows that at a duty rate of 20%, job losses in the EU could amount to 115,600 in the first year, costing €4.740 billion. Over three years, 175,500 jobs would be at risk, incurring a cost of €18.4 billion.

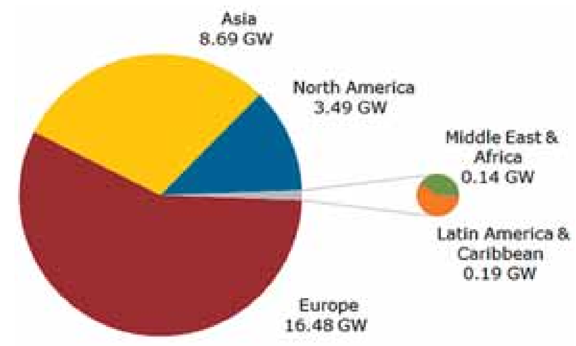
Source: Images_of_Money

A duty rate of 60% could result in a loss of €7.860 billion over three years.

By comparison, a duty rate of 60% could result in 193,700 job losses after the first year resulting in a loss of €7.860 billion, over three years this would rise to 242,000 jobs, costing €27.2 billion. ProSun has asked the Commission to impose tariffs of up to 120% stating this would allow EU producers to operate profitably.

Market Trends News Focus

NPD Solarbuzz dampens PV growth levels for 2012



Source: NPD Solarbuzz

NPD Solarbuzz said that European demand was 16.48GW, almost 60% of global demand in 2012.

The expectation that PV installations would reach 32GW in 2012 has been dampened by a new report from NPD Solarbuzz. According to the market research firm, PV demand in 2012 reached 29GW, up only 5% from 27.7 GW in 2011. Notably, the growth figure is the lowest and the first time in a decade that year-over-year market growth was below 10%.

According to the report, PV supply remains 50% higher than demand in 2012, despite another annual record level of growth. The 29.0GW of demand added during 2012 was said to be nearly 30% of all installed PV capacity at the end of 2012.

NPD Solarbuzz said that European demand was 16.48GW, almost 60% of global demand in 2012. Asia proved to be the second strongest market, generating 8.69GW of demand, notably much coming from China in the second half of 2012.

The Americas provided 3.68GW of demand, or 13% of global demand in 2012. Yet it should be noted that California provided more than one-third of all PV demand from the entire Americas region during 2012.

Source: BNRG Renewables

PV demand in 2012 reached 29GW, up only 5% from 27.7 GW in 2011.

Market pressures squeezing BOS manufacturers

Pressures to drive down costs will push many balance of system (BOS) manufacturers "to the edge" and ultimately result in a less crowded market, according to new research.

A report by GTM Research said that with BOS technologies being targeted over PV modules to deliver the next round of cost reductions for solar, the market will become increasingly tough for many players.

Solar industry fallout to peak in 2013

The highly volatile PV industry is notoriously difficult to predict, yet that has not stopped market research firm IHS in providing its key ten predictions for the industry in 2013. Starting with its market forecast as the priority pick, IHS said that it expected double-digit installation growth in 2013, which could see installations in the mid-30GW range.

Source: epSos.de

2013 revenue is expected to be in the range of US$75 million.

However, due to falling prices continuing global industry revenue is expected to continue to fall. The market research firm expects 2013 revenue to be in the range of US$75 million if 2013, down from a forecasted US$77 billion in 2012. According to IHS, industry revenue peaked at US$94 billion in 2011.

Asia Pacific solar demand to grow 50% in 2013

The Asia Pacific region is forecast to grow to 13.5GW in 2013, representing a 50% year-on-year growth rate, according to the latest NPD Solarbuzz Q1'13 Asia Pacific Major PV Markets Quarterly report.

However, a number of issues beset the region; not least trade wars that are potentially leading to import duties or restrictions as well as potential policy changes supporting PV installations.

China's closed downstream solar market set to open

Foreign PV module manufacturers may not get a look-in on the closed Chinese downstream market but balance-of-system (BOS) suppliers could find the market lucrative, according to a report from NPD Solarbuzz.

The BOS market in China is set to boom on the back of more than 7GW of installations expected in 2013. The ground-mounted segment would continue to dominate PV demand in China with a market share of 57% this year. This continues to be driven by large-scale commercial and utility projects in the Northwest region, according to the market research firm.

44% third-quarter surge for US PV

The US solar PV market grew by 684MW in the third quarter of 2012, 44% more than in the same period last year, according to a report by Solar Energy Industries Association (SEIA) and GTM Research.

This quarter marked the third largest on record for the US PV industry, raising the total installed capacity through the first three quarters of the year to 1,992MW, surpassing 2011's annual total of 1,885MW. SEIA and GTM Research expect 2012 growth to top 70% with a record 3.2GW of solar installed – enough to power more than half a million average US homes.

The residential PV sector continues to be the most stable growth segment of the US solar market, installing an all-time high for a quarter of more than 118MW, a growth of 12% over Q2 2012.

Mexico, Chile, and Brazil to dominate PV demand in Latin America

Although emerging PV markets of Latin America and the Caribbean are set for 45% CAGR's through 2017, Mexico, Chile, and Brazil are set to become the mainstream markets, absorbing nearly 70% of demand, in Latin America according to a new report from NPD Solarbuzz.

According to the market research firm, PV project applications in Latin America and the Caribbean topped 6GW in 2012. The market is therefore expected to be dominated by ground-mount installations compared to rooftop as seen in key markets in Europe. NPD Solarbuzz is forecasting that 60% of PV demand by 2017 in the region will be ground-mounted.

SolarCity dominating booming US residential PV market

The third-party financing business model is dominating the booming US residential market, according to the latest report from GTM Research.

Despite a slew of new entrants and the expectation of more to follow, the residential third-party ownership vendor that currently dominates the landscape is SolarCity, one of the pioneers of the model. SolarCity was said to have a market share (18.8% in Q3 2012) more than double the next largest player, Verengo Solar in 2012.

China to increase investment in domestic market

A much anticipated cash injection from the Chinese government into its domestic market was announced by Premier Wen Jiabao in December 2012.

Jiabao said that although the Chinese industry has developed rapidly over the past few years, excess capacity and an excessive foreign import philosophy has caused operating difficulties.

The proposed measures include putting in place a mechanism to encourage corporate M & As to accelerate R & D. In addition, the Chinese Ministry of Finance has earmarked US$9.5 billion of funding for solar power.

MENA countries to hit nearly 3.5GW by 2015

Saudi Arabia and Turkey are expected to dominate the solar market in the Middle East and North Africa (MENA) region, according to GTM Research's latest report.

Produced in collaboration with the Emirates Solar Industry Association

Source: Fotopedia

Chile is set to become a mainstream market by 2017.

News

Source: Argenberg

Saudi Arabia and Turkey are expected to dominate the solar market in the Middle East and North Africa.

(ESIA), the reports highlights insolation, grid prices and electricity demand as the fundamental factors that will make Saudia Arabia the MENA region's first gigawatt-scale market by 2015.

The report also forecasts Turkey to be the second strongest market in the region in 2015 and beyond, as favourable renewables policies and previous wind installation experience is expected to translate into greater solar demand.

Business News Focus

IFC issues US$1 billion bond for 'climate-friendly' projects

IFC, a global development institution for the private sector and a member of the World Bank Group, has issued a US$1 billion green bond which will be used to support IFC "climate-friendly" projects in developing countries.

The three-year bond – which is said to be the largest green bond issue to date – is available to investors around the world. The bond was oversubscribed and has been sized to meet the demand from an increasing number of investors keen to support renewable energy, energy efficiency, and other climate-friendly projects.

In IFC's 2012 financial year, the company invested US$1.6 billion in climate related investments, of which 70% was related to energy efficiency and renewable energy projects. By the 2015 financial year, IFC expects to double the US$41.6 billion figure to approximately US$3 billion per year.

Power-One impacted by 32% sales decline in Europe; cuts 300 jobs

PV inverter specialist, Power-One reported fourth quarter revenue of US$192 million, within revised guidance but sales declined 32% in Europe, forcing the company to adjust production to demand with the planned loss of 300 jobs.

On a geographical basis, EMEA represented 76% of RE revenue with 28% of total revenue coming from Italy, 17% from Germany and 31% from the rest of the region. Asia Pacific represented 9% of total RE revenue and North America was 15%.

Power-One said it expected Q1 2013 revenue to be in the range of US$175 million to US$200 million, a wide range due to seasonality and an expected subdued market in Germany and Italy.

Panasonic's PV sales in Europe remained weak in FY third quarter

Panasonic reported its Energy segment sales, which includes HIT PV modules of ¥142.3 billion (approx. US$1.5 million) for its FYQ3 2013.

Panasonic reported energy segment sales for the first nine months of ¥434.8 billion, down 6% from ¥461.8 billion in the same period a year ago.

The company said that fixed cost reductions and streamlining material costs improved segment profitability ¥6.4 billion compared with a loss of ¥16.7 billion a year ago.

Panasonic's overall forecast for fiscal 2013 remains unchanged from the previously revised forecast announced at the end of November 2012.

JinkoSolar issues US$128 million bond in China

Tier 1 module manufacturer, JinkoSolar has successfully placed a US$128 million in bonds after approval from the Chinese National Development and Reform Commission's (NDRC) Financial Division. JinkoSolar said that the proceeds from the bonds would be used for capital expenditure and working capital purposes.

Solar venture capital investments fall by almost 50%

Investments plunged to US$992 million in 2012 compared to US$1.9 billion the previous year, representing the lowest amount since 2007, reports consulting firm Mercom Capital.

Venture capital (VC) financing, the investment in early-stage, high-potential, growth companies, in Q4 2012 was US$220 million. The leading VC deal in this quarter was concentrating solar thermal company BrightSource Energy with US$83.6 million.

BrightSource also led the way in the downstream category, which benefitted from low module prices. The total investment was US$269 million. The top five VC funding deals in 2012 were BrightSource Energy, for US$83.6 million, SolarCity, a solar lease firm, for US$81 million, CIGS company Nanosolar for US$70 million, solar lease company Sunrun for US$60 million, and MiaSolé, a CIGS company, for US$55 million.

Thin-film companies saw the largest amount of VC funding in 2012, although the total fell 47% to US$314 million compared to almost US$600 million in 2011.

Feed-in Tariff News Focus

EPIA demands Commission take action against member states for renewables cut-backs

The European Photovoltaic Association has asked the European Union to take action against member states curtailing support to the renewables industry.

More than 70 companies and associations in the solar PV electricity sector have co-signed a letter to European Energy Commissioner Günther Oettinger, calling on the EU to take action against member states that are enacting retroactive measures or moratoria on support schemes for renewables.

WTO: Ontario domestic content requirement discriminatory

The Canadian province of Ontario has been charged with violating World Trade Organization rules through its domestic content tariffs.

The European Union and Japan brought its complaint of alleged Ontarian prejudice against foreign solar developers to the WTO last year. The countries claimed Ontario's domestic content requirement was in violation of the General Agreements of Tariffs and Trade (GATT) as well at the Trade-Related Investment Measures (TRIMs). Canada has appealed these charges.

The WTO has recommended that Canada put its house in order and bring its measures into conformity with its obligations under the TRIMs Agreement and the GATT 1994 to offer indiscriminate subsidies.

Source: Argenberg

The EU and Japan have brought a complaint regarding Canada's domestic content allowance to the WTO.

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Deconstructing solar photovoltaic energy: Part 2

Antonio Alvarez & **Elisa Yoo**, Acero Capital, Menlo Park, California, USA

ABSTRACT
This is the second and concluding part of a study on the solar photovoltaic market. In the first part, photovoltaic energy was contrasted with other energy sources used to generate electricity, and cost points necessary to produce a sustainable photovoltaic market were identified. In this second part, learning rates required to attain those cost points are provided. The paper concludes by examining a scenario in which 15% of the world's electricity in 2035 is generated using photovoltaic energy, and frames the challenge from both global investment and profitability perspectives.

Introduction

The previous edition of *Photovoltaics International* presented the first part of a study on deconstructing the PV market and its cost structure into logical components in order to bring some clarity to critical issues facing the industry, which is currently going through a turbulent period [1]. One critical question is what (and when) new disruptive technologies will be required in each of the three categories – cell, module and balance of system (BOS) – to maintain the necessary cost learning rates to continue to drive PV-generated electricity from today's US$0.20–0.40/kWh to ~US$0.10/kWh. The search for answers has led to investments in alternative thin-film technologies (primarily CdTe and CIGS) as well as monolithic and frameless methods for (automated) module construction, etc. Some of these technologies will become mainstream – most will not.

With the foundation having been laid in Part 1 of the study [1], Part 2 begins with a cost breakdown of the PV energy supply chain from system installation to cell manufacturing. The PV market evolution is then reviewed, and the likelihood of 15% of the world's electricity being generated by PV energy is discussed.

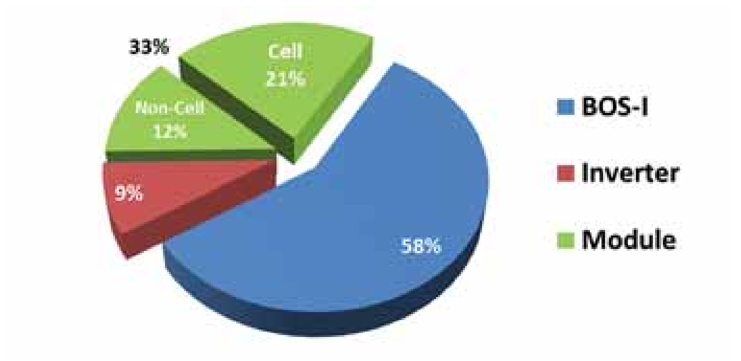


Figure 1. Breakdown of PV installation costs.

Source: Acero Capital compilation

PV installation costs

The breakdown of installation costs (in terms of the average selling price ASP) is shown in Fig. 1; these costs represent the aggregation of the selling prices [2–4] relating to:

- BOS not including the inverter (BOS-I): 50–60%
- Inverter: 7–9%
- Module: 30–35%
- Cell: 60–70% of module

Historically the PV module has constituted 45–50% of the installation ASP, but this percentage has dropped recently into the low thirties, as module ASPs have fallen at a much faster rate than the BOS components.

Between 2001 and 2011, installation costs in the USA dropped over 50% – from $10/W to approximately $4.5/W [4–6]. European installation costs, while ~25% lower because of higher volumes, exhibited a similar decline during the same period [7] (Fig. 2). In both cases, this translates into a learning rate of ~13%; in other words, on a dollar per watt basis, the price charged for a PV installation fell ~13% each time the installed capacity doubled. The price drop has been more dramatic since 2009 [7]. Isolating the period from 2009 to 2012 (extrapolated), installation costs had a learning rate of 28% – more than double the 10-year learning rate. The reason for the accelerated learning rate is primarily the precipitous drop in module pricing. On the basis of the market growth assumptions presented later in this article, the learning rate required to achieve a blended $1.45/W installation price (equating to a levelized cost of electricity LCOE of ~$0.10/kWh) within 10 years (2022) is 24%; this is significantly greater than that of the past 10 years, but less than the observed rate over the past three years. Given the economic challenges that the industry has had in digesting the past three years of 28% cost-reduction learning rates, maintaining a learning rate of 24% for the next 10 years appears daunting.

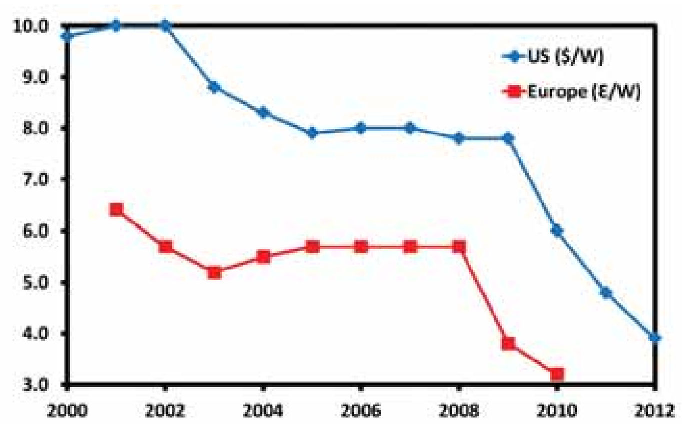


Figure 2. Historical installation costs in the USA and Europe.

Source: LBNL (September 2011); SEIA (June 2012); EPIA (September 2011)

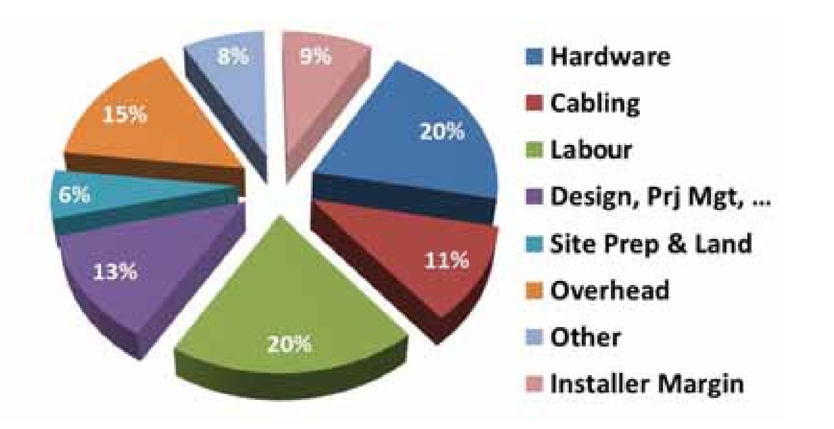
"The learning rate required to achieve a blended $1.45/W installation price within 10 years (2022) is 24%."

In addition to the conventional volume-based learning rate, installation cost (not surprisingly) is a strong function of the market segment. Residential prices are considerably higher than commercial/industrial prices, which in turn are considerably higher than utility prices. This is primarily a function of scale and the ability to leverage BOS costs across a larger installation. At $3/W, average PV utility installation costs at the end of 2011 were just above the $2.50/W inflection point [1], and the best-in-class PV utility installations (>20MW) were already there [7,8]. The utility-scale installation average is likely to have achieved the $2.50/W cost point in 2012.

PV BOS costs

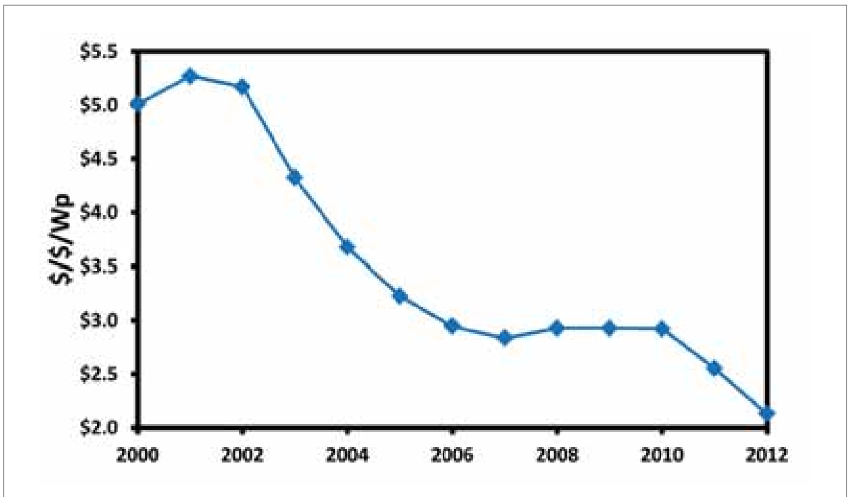
PV BOS costs excluding the inverter (BOS-I) typically make up 50–60% of PV installation ASP. Over 65% of the BOS-I costs are hardware and labour related and consist of a combination of costs associated with racking, mounting, cabling, etc. (30%), labour (20%) and design/project management (13%) [2,9–11] (Fig. 3). While none of these items 'scale' in the conventional sense, there is a great deal of effort being placed, especially within the utility sector, in standardizing designs, reducing overheads and streamlining installations in order to further reduce costs. Improvements will come both in physical design (electrical systems, hardware standardization, structural design for low-labour installation, etc.) and in business processes (improved project management, standardization of installation best practices and system design, streamlining of the permit process and other overheads, site preparation standardization, etc.).

Over the period 2001 to 2011, worldwide BOS prices have been cut in half, from approximately $5.0/W to $2.6/W [6,7,9] (Fig. 4). This equates to a learning rate of ~12%: i.e. BOS prices dropped 12% each time the installed capacity doubled. However, costs varied significantly depending on the location and the type of installation: BOS costs for utility-scale installations, for example, were as low as $1.40/W towards the end of 2011 [10].



Source: Acero Capital compilation

Figure 3. Breakdown of PV BOS costs (excluding inverter).



Source: Acero Capital compilation

Figure 4. Historical BOS $/W ASP.

Under the assumption that the PV BOS recovers to 60–65% of installation ASPs going forwards, the BOS price required to support a $1.45/W installed price point (equating to an LCOE of ~$0.10/kWh) is $0.80–0.94/W. The learning rate required to achieve this range of BOS price over the next 10 years is ~25%. Given the historical learning rate of ~12% and the makeup of BOS costs, achieving a 25% learning rate will be challenging and could well be the limiting factor in PV installation cost reductions. As a consequence, efforts have been made to systematically break down BOS costs in order to determine the necessary steps to achieve a BOS cost of $0.88/W [11,12].

PV module costs

Historically, PV module ASPs have constituted 40–50% of the overall PV installation price. But, because of the precipitous drop in module ASP over the past three years, this percentage has fallen to 30–35%. Over 60% of the module cost is made up of the cost of the cells (Fig. 5). Most of the balance of the module costs (~25%) is attributable to basic materials such as EVA, backsheet, frame, glass, J-box, cable, ribbons, etc. [3,4,13]. The labour contribution tends to be relatively small, of the order of 1%. It follows that the focus for module cost reductions will be on material elimination (e.g. frameless modules) or reduction, and on material cost reductions (in particular reducing the cost of the backsheet and EVA). Nevertheless, given that the cell cost constitutes over 60% of the module cost, cell cost reduction and efficiency improvement need to be two of the major drivers in reducing module cost per watt.

"Cell cost reduction and efficiency improvement need to be two of the major drivers in reducing module cost per watt."

From 2001 to 2011, worldwide module ASPs fell by 60%, from approximately $3.00/W to $1.25/W [14,15] – a learning rate of ~13% (Fig. 6). However, almost all of the reduction in ASP has occurred since 2008, corresponding to a learning rate over the past four years of ~36% (or ~32% since 2009). The two main reasons for the recent doubling of the learning rate are:

1. Polysilicon market price dynamics (undersupply to oversupply – prices held up and then dropped rapidly).

2. Competitive response to the PV market potential, resulting in overcapacity and a corresponding narrowing of the cost-to-ASP gap.

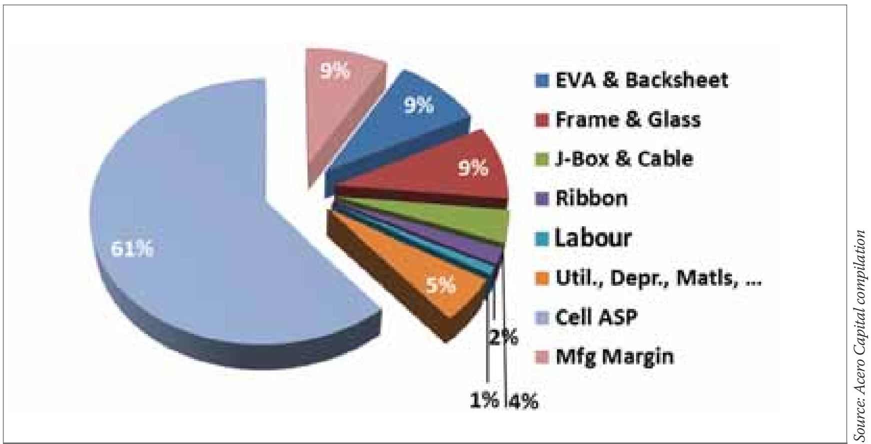


Figure 5. Breakdown of PV module ASP.

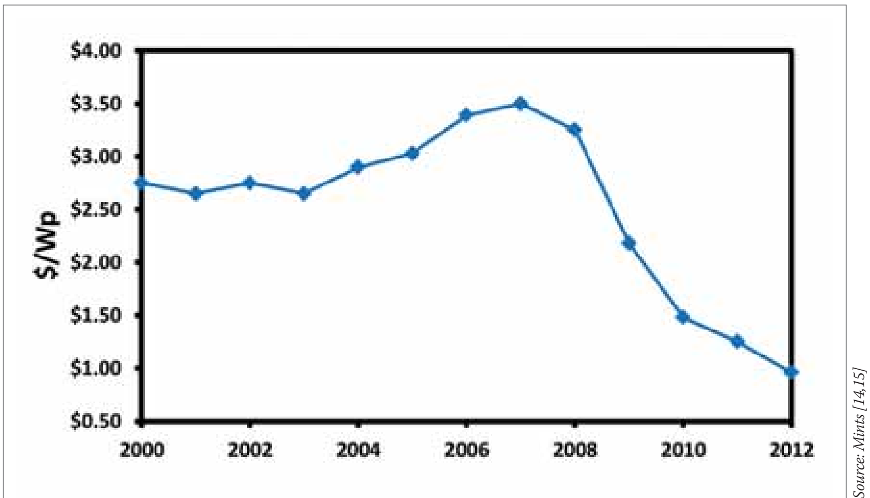


Figure 6. Historical module ASP to first buyer.

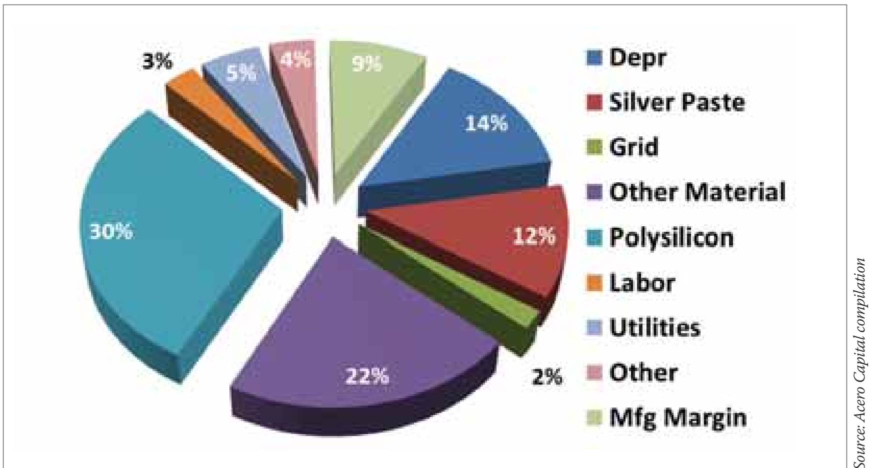


Figure 7. Breakdown of PV cell ASPs.

This market dynamic continued into 2012: as of May 2012, module prices had dropped to \$0.70–0.90/W [16]. Given the industry fallout and resulting low module margins, it is not clear how much longer this pricing rate decline can continue. Nonetheless, given the amount of capacity that is currently in place, it would not be surprising if the learning rate remained at ~30% through 2015 or 2016.

It is likely, however, that the longer-term cost learning rate will fall somewhere in between the last ten-year and the more recent three-year learning rates, i.e. ~22%, which turns out to be the 30-year learning rate [9]. Assuming that the PV module ASP rebounds to 35–45% of the installation price, the module ASP required to support a \$1.45/W installation price point (equating to an LCOE of ~\$0.10/kWh) would be \$0.51–0.65/W. The learning rate required to achieve the bottom range of this module price within the next ten years is ~18%. While this learning rate appears achievable, it will need to be driven primarily by reductions in cell cost and improvements in cell efficiency.

PV cell costs

PV cells typically make up 60–75% of PV module costs. Material costs, including polysilicon, account for approximately 65% of the cell cost [3,4,16] (Fig. 7). And, in spite of the recent drop in pricing, from well over \$100/kg to \$24/kg, polysilicon remains the largest component of cell cost at ~33%. Cell costs are typically broken down into substrate (\$0.15–0.18/W, depending on the cost of polysilicon), wafer (~\$0.18/W) and cell conversion (~\$0.19/W) costs [17]. Needless to say, cost reductions in all three areas are being aggressively pursued. These cost reductions fall into three general categories:

1. Efficiency improvements: minimizing photon, carrier or electrical losses [18].

2. Material cost reductions: use of poly-Si and minimizing wafer thickness if Si-based, material consumables, replacement or reduction of silver, etc.

3. Productivity improvements: equipment throughput/cost, yields, uptime, labour (e.g. operators and/or maintenance for each piece of equipment), floor space, etc.

In the case of Si-based cells, today's dominant technology, a variety of options can currently be found in prototype lines: selective emitters, textured front surfaces, heavily doped rear surfaces and rear-contacts, and increasing use of n-type substrates and, in more extreme cases, approaches such as emitter or metal wrap-through structures (EWT, MWT) [18,19].

Between 2001 and 2011, worldwide PV cell ASPs dropped by more than half, from approximately \$2.20/W to \$0.90/W; as of May 2012 they were down to \$0.51/W [16,20] (Fig. 8). This translates to a learning rate of ~15%: i.e. cell costs fell 15% each time the installed capacity doubled. From 2009 to 2012, however, this learning rate has more than doubled, reaching ~38%. Under the assumption that the PV cell price remains at ~70% of the module price going forwards, the cell price required to support a \$0.51–0.65/W module ASP point (or support an LCOE of ~\$0.10/kWh with the BOS cost assumed above) is \$0.36–0.46/W. The learning rate required to achieve the bottom range of this cell price within 10 years (2022) is ~11%, which is not particularly aggressive compared to historical learning rates. On the other hand, since improvements in cell cost and cell efficiencies drive downstream cost reductions, the pressure to achieve learning rates better than 11% will remain intense.

"The cell price required to support a $0.51–0.65/W module ASP point is $0.36–0.46/W."

A summary of the various learning rates discussed above for the historical periods 2001–2011 and 2009–2012, as well as the learning rate required to achieve a $1.45/W installed ASP by 2022, is provided in Table 1 and graphically illustrated in Fig. 9. It is clear that the industry has not been characterized by a single learning rate in the past 12 years. Rather, there was a relatively slow learning rate from 2001 to 2008, followed by a rapid acceleration in the last four years. As discussed earlier, pricing in this recent period was driven by a precipitous drop in polysilicon pricing as well as a surge in capacity resulting in an imbalance between supply and demand. What is interesting is that using 2012 as the starting point, the learning rates required to achieve the $1.45/W installation ASP benchmark by 2022, consistent with an LCOE of $0.10/kWh, appear to be well within the capability of the front end of the industry (module and cell). But the learning rate requirements for BOS and therefore the complete system installations are significantly higher than what the industry has managed to deliver over the past 10 years. The implications are twofold. First, unless the BOS segment of the PV supply chain changes from 'business as usual,' it will be difficult to achieve the $1.45/W price point by 2022. Second, the pressure on reducing module and cell costs through accelerated learning rates will continue to offset what ideally would be a proportionate contribution from the BOS segment.

Deconstructing the total available PV market

The PV market has been growing at a compounded annual growth rate of ~30% over the past 10 years [21] (Fig. 10). However, a geographic deconstruction of this growth reveals that it has been fuelled by asynchronous growth of individual markets that have in turn been fuelled by starts and stops of subsidies [21] (Fig. 11). Thus, while on the surface the PV market appears relatively smooth and 'untroubled,' there has been considerable turmoil beneath the surface. Fortunately for the industry, the changes in individual country subsidies that have produced the underlying market turmoil have been offset in time, with the end result being that the overall industry has continued to grow at a rapid rate [22]. But to achieve continued growth, unsubsidized PV costs have to come down to the point that

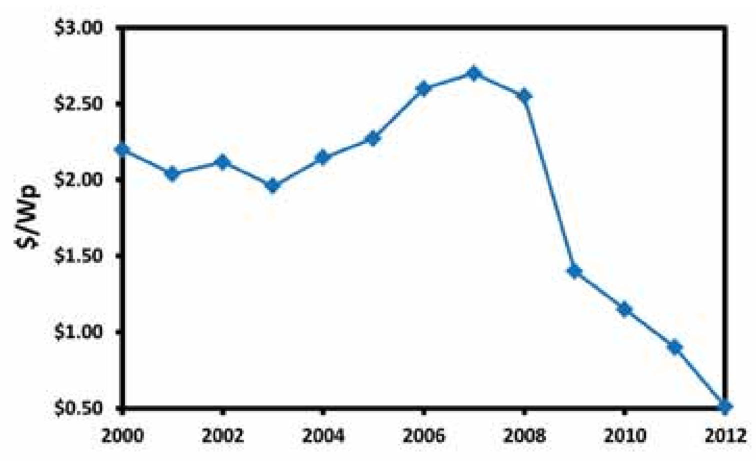


Figure 8. Historical PV cell ASP.

Source: Acero Capital compilation

	2001–2011 [%]	2009–2012 [%]	2012–2022 [%]
Install	13	28	24
BOSI	12	14	25
Module	13	32	18
Cell	15	38	11

Table 1. Summary of historical PV component learning rates and forward-looking learning rates required to achieve $1.45/W by 2022.

Source: Acero Capital compilation

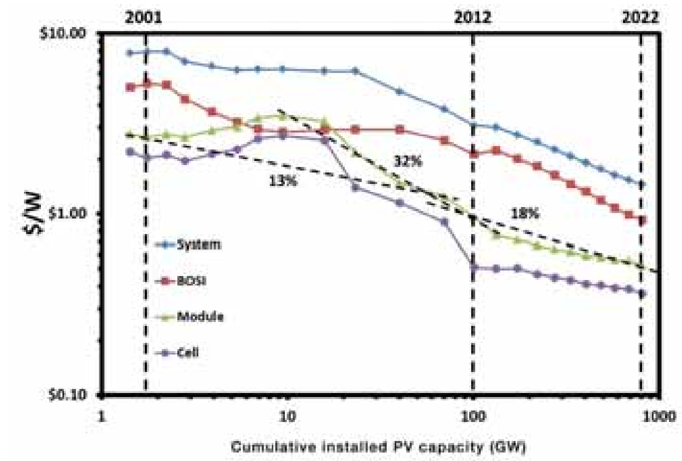


Figure 9. Graphical summary of PV component learning rates.

Source: Acero Capital

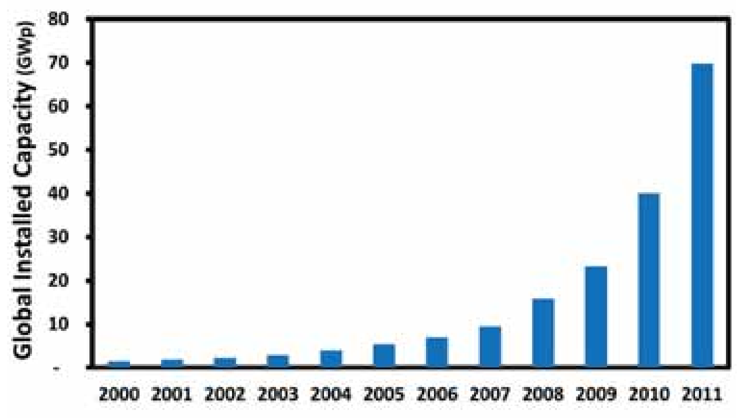


Figure 10. Evolution of the solar market.

Source: EPIA, May 2012

electricity generation from PV makes financial sense. The cost of subsidizing gigawatt levels of PV generation capacity has become prohibitive for most countries, especially in the light of the overall world macroeconomics. It follows that to achieve a self-sustaining growth trajectory, typical of most unsubsidized markets, the cost of PV electricity generation must stand on its own merits. As noted in the previous section, the industry is rapidly approaching a cost tipping point that will enable revenue sustainability, if not always profitability.

> "To achieve continued growth, unsubsidized PV costs have to come down to the point that electricity generation from PV makes financial sense."

Market Watch

Aside from geographic classification, the PV market is commonly divided into three segments: 1) residential, 2) non-residential (industrial/commercial) and 3) utility/ground-based. Residential installations tend to be rooftop systems, and in the USA these average ~6kW (Table 2). Utility-scale installations are typically ground-mounted and increasingly single-axis tracker systems, and have been getting larger over time. The 2012 US utility segment average (through May 9 2012) is ~10MW per installation – double the 2009 average installation size. Finally, industrial/commercial US installations average ~85kW.

Of the three installation types, the utility segment is the fastest growing, with a growth of ~760MW in 2011, and over 3GW of projects in construction [5] – almost three times that in 2010. Note that, from an installation cost perspective, in 2011 there was approximately a $1/W difference between the three segments. This translates to the residential segment having the smallest total available market (TAM) at ~$1.7 billion, with the non-residential having the largest at ~$3.9 billion [5].

Finally, the market can also be divided into grid-connected and off-grid segments. In the USA, as in most of Europe and increasingly Asia and the rest of the world, the bulk of the PV market is grid connected: more than 95% of the 2010 US installations and more than 80% of the cumulative US installations were grid connected [23].

How big can the PV market get?

Rather than providing a PV market forecast (this has been demonstrated to be a losing proposition, with forecasts prepared over the past few years quickly becoming obsolete), the question has been turned around and now becomes: what investment would be necessary to achieve 15% of the world's electricity generation from PV by 2035? This scenario requires ~3800GW of installed PV generation capacity and a ~$4.9 trillion investment (Table 3). Annualized this would require building every year for 25 years the equivalent of ~1500 100MW PV power generating plants. This is no small task given that there are only a handful of 100MW-capacity PV power plants in existence today [26]. The resulting invested capital required averages out to ~$200 billion per year. From a market perspective, the result is a TAM growth from ~$100 billion to over $300 billion. At the module level this would translate to a TAM growth from ~$30 billion to ~$125 billion, and a cumulative spending of ~$1.6 trillion, equivalent to ~35% of the total investment in PV installations. Finally, at the cell level the TAM would grow from ~$20 billion to ~$90 billion, with a cumulative spending of ~$1.2 trillion, which is equivalent to ~70% of the total spending for modules. As an aside, the land mass required (assuming ~33km^2/GW) would be roughly 20% larger than either Cuba or South Korea. While not insignificant, this would still be a relatively small percentage (less than 0.1%) of the world's land mass.

Putting a 15% PV market into perspective

While a $4.9 trillion investment is enormous, it is important to put this expenditure into context. It is estimated that $10 trillion will be invested in incremental electricity generation over the period 2010–2035 [27] (Fig. 12). The relevant question is therefore: if the world's economies were to invest $4.9 trillion in PV electricity generation over this 25-year period to achieve the 15% PV metric, would this make economic sense compared with investments in alternative sources of electricity generation?

From an invested capital perspective, a simple breakeven argument would imply that, since the $4.9 trillion PV investment would be nearly half of the projected $10 trillion dollars to be spent in incremental electricity generation, PV should provide half of that incremental electricity capacity. With the PV cost roadmap cited, for $4.9 trillion, or 49% of the total investment in electricity production, in this model PV power plants would supply ~38% of the incremental electricity (Table 4).

Looking only at capital expenditure, either a $1.1 trillion 25-year subsidy (~$40 billion/year) or an installed cost lower

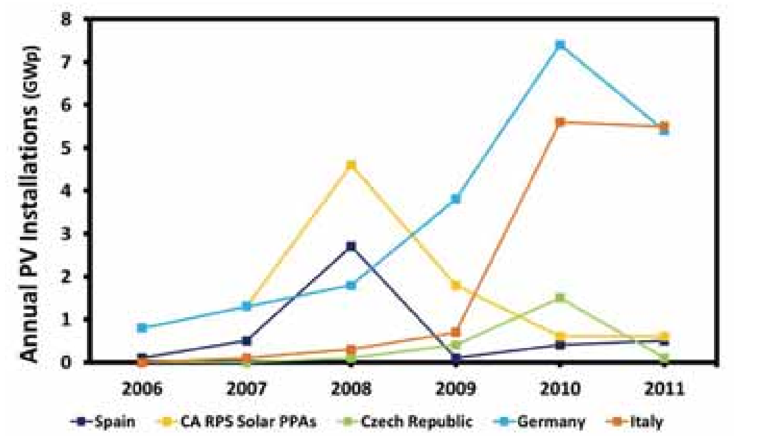


Figure 11. Breakdown of the solar markets (CA RPS = California renewables portfolio standard).

	2010 Installations			2011 Installations			2010–2011 MW
	Number	Avg size [kW]	MW	Cost [$/W]	TAM [$bn]	MW	Growth [%]
Residential	45,570	6	266	6.00	1.67	279	5
Non-residential	4,486	85	367	5.00	3.93	785	114
Utility	30	8,500	255	3.50	2.65	758	197

Table 2. Summary of US grid-connected market segmentation by type.

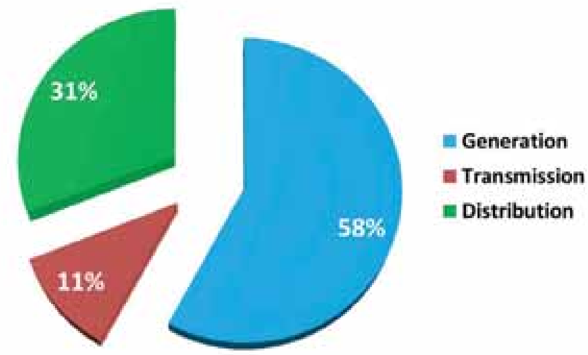
Source: Acero calculations; SEIA (March 2012)

		2010	2015	2020	2025	2030	2035
WW electricity	T kWh	21.3	22.7	25.5	28.7	31.9	35.2
WW solar	G kWh	52	294	777	1,756	3,217	5,295
Solar %	%	0.25	1.3	3	6	10	15
Solar capacity	GWp	40	220	576	1,285	2,325	3,778
New 100MWp plants	-	n/a	1,807	3,558	7,087	10,397	14,532
New plants/year	-	n/a	361	712	1,417	2,079	2,906
Capital cost/year	$bn	n/a	107	135	192	237	304
WW land used	km^2	1,327	7,349	19,209	42,831	77,486	125,926
% of WW area	%	0.001	0.005	0.013	0.029	0.052	0.085
Cum. plants			1,807	5,365	12,451	22,848	37,380
Cum. capital ($bn)			533	1,206	2,168	3,355	4,874

Source: Acero calculations

Table 3. Required solar capacity to achieve 15% PV generation share of the market by 2035. Assumptions: 1) 2%/year growth in worldwide electricity generation [24]; 2) reduction in installed PV costs from $3/W to $1/W (~20% learning rate); and 3) improvement in capacity factor for PV-generated electricity from 15% to 16% [25].

than modelled ($0.77/W rather than $1.02/W by 2035) would be required to merit that 15% of the world's electricity be generated from PV on a purely invested capital basis. Obviously there are well-known arguments beyond invested capital alone as to why it can still make sense to invest at this level in PV generation capacity [28]. Nonetheless, a scenario (or goal) of meeting 15% of the world's 2035 electricity generation with PV will be quite challenging from both financial and logistical perspectives. Consequently, it should not be surprising that the US Energy Information Administration (EIA) forecast (Fig. 13) predicts 7% for *all* renewable generated electricity, a figure much less than the 15% PV scenario of Table 3. The end result will play out over the next 10–15 years, and most likely the actual figure will fall somewhere between these two extremes.



Sorce: World Energy Outlook 2012

Figure 12. Investments in power – total = $16.9 trillion (generation = $10 trillion).

Financial metrics and profitability expectations

While it is apparent that the revenue potential in the PV market is tremendous, the profitability outlook is less clear. Given the capital intensiveness of the PV power business, proper asset utilization is critical. A review of historical return on assets (ROA) percentage and earnings before interest, taxes, depreciation and amortization (EBITDA) margin from US, Chinese and German PV public companies provides insight into past performance and enables a simple model to be constructed that companies can benchmark against. For example, in order to achieve a positive ROA, a minimum EBITDA margin of 5% (and preferably 10%) is necessary (Fig. 14(a)). This in turn corresponds to a gross margin (GM) of ~20% (Fig. 14(b)). As the PV industry matures, these are likely to be metrics on which surviving companies will converge.

Since the gap between module ASP and cost is currently less than 20%, it is reasonable to assume that the module ASP learning rate in Table 1 for 2012–2022 applies equally well to module cost. It follows that the ~$0.67/W and $0.52/W module price points, corresponding to $2.50/W and $1.45/W installation prices, dictate a $0.54/W and $0.42/W module cost and a learning rate of ~18%+ in order to achieve 20% GM.

> "A scenario in which 15% of the world's 2035 electricity is generated by PV requires a cumulative $4.9 trillion capital investment in PV generation."

Conclusion

Electricity consumption in the USA starts to increase dramatically at a price point of approximately $0.18/kWh, and

		2010–2015	2015–2020	2020–2025	2025–2030	2030–2035	2010–2035
Incremental electricity	G kWh	1,400	2,800	3,200	3,200	3,300	13,900
Incremental PV	G kWh	241	484	979	1,461	2,078	5,243
PV % of increment	%	17	17	31	46	63	38

Source: Acero calculations

Table 4. Percentage of incremental electricity generated by PV.

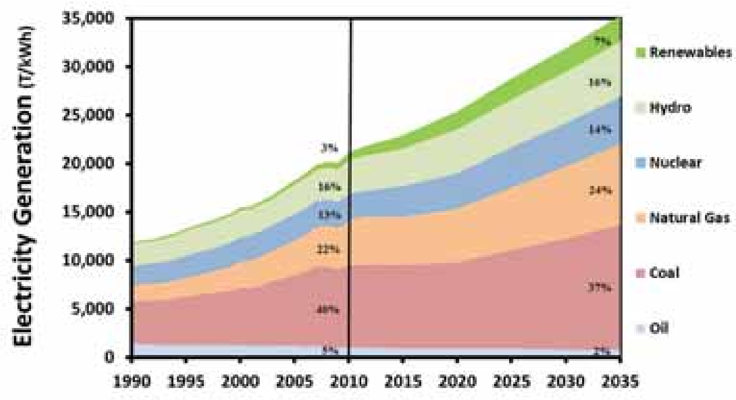


Figure 13. Forecast global energy sources for electricity generation.

Source: EIA, IEA, BP

approximately half of the USA's electricity is purchased at a price above $0.10/kWh. Under some simplifying assumptions, the $0.18/kWh and $0.10/kWh translate into the following respective price points:

- ~$2.50/W and $1.45/W for installation
- ~$0.67/W and $0.52/W for modules
- ~$0.47/W and $0.36/W for finished cells

To provide a reasonable return on capital a 20% GM is required. This implies a $0.54/W and $0.42/W module cost for $2.50/W and $1.45/W installation costs respectively. The industry is expected to price modules at ~$0.67/W by 2014 or 2015. The modelling carried out suggests that the second price point of $0.52/W is achievable by 2022. PV module and/or wafer suppliers that survive must have credible paths to the upper end of these ranges within the next 18–24 months, and to the bottom end of these ranges by 2022.

From a supply chain perspective, the biggest challenge in achieving the necessary cost targets are in the installation/BOS segment. This will continue to put pressure on the cell and module portions of the PV supply chain to carry a disproportionate load of cost-reduction burden.

Finally, a scenario in which 15% of the world's 2035 electricity is generated by PV requires a cumulative $4.9 trillion capital investment in PV generation (i.e. installations). This would be a massive infrastructure project, requiring the equivalent of ~1500 100MW PV plants be built each year through 2035. Annualized this would average out to ~$200 billion per year. The PV module and cell spending to support this infrastructure build are ~$67 billion and ~$47 billion per year respectively. In order to realize the 15% scenario, either near-term cost reductions beyond what are currently modelled or significant continued subsidies will be required.

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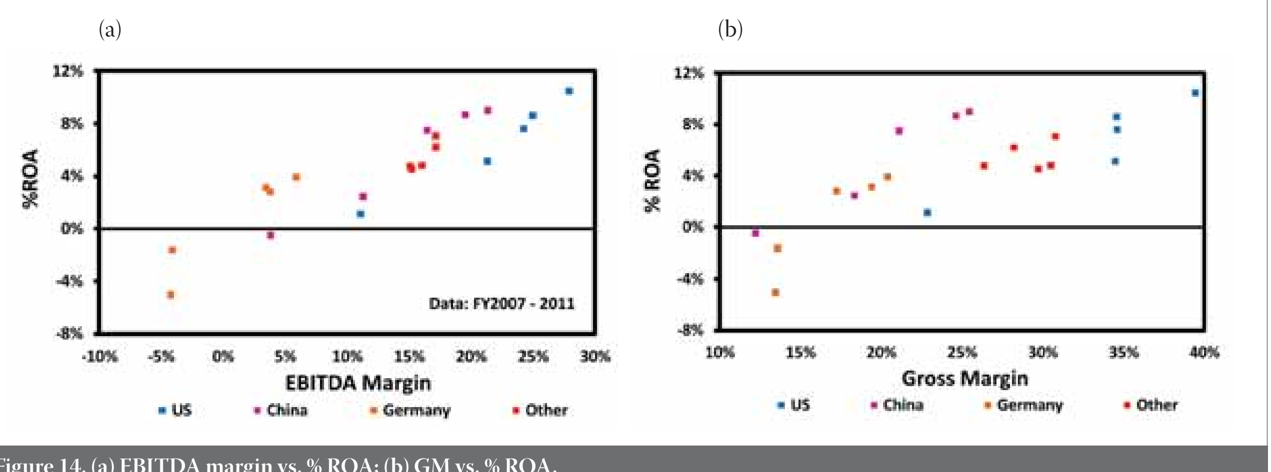

Figure 14. (a) EBITDA margin vs. % ROA; (b) GM vs. % ROA.

Source: Company information; Public filings

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The PV-Tech Blog

By **Mark Osborne**, Senior News Editor, *Photovoltaics International*

Yingli Green's secret sauce

Yingli Green has become the largest PV module supplier in 2012. News that the company revised up its shipment guidance for the fourth quarter and full year followed a trend in each quarter of 2012 that it was out-selling Suntech, which has been the leading supplier since 2010.

Final confirmation came in February 2013, when Yingli Green reported preliminary shipments of approximately 2.3GW, significantly higher than the previous guidance of 2.1–2.2GW.

But what has driven this success? Is there some kind of secret sauce? Can they maintain momentum and dominate the rankings for the long-term?

In some respects it is hard to believe that in 2004 Yingli shipped a mere 4.7MW of modules as it started ramping up its first manufacturing facility. Arguably, it was not until 2008 that the company reached any meaningful shipment levels (281.5MW) and really took off from there.

What is remarkable is that each year after 2008, Yingli has made quantum leaps in its shipments, despite increased competition, the financial crisis and two years of massive industry overcapacity. Other than Jinko Solar's rapid ascent in shipments in 2010 and 2011, no other module manufacturer has built and maintained such momentum.

Sweet spot

What is also remarkable is that Yingli was not a remarkable company. Its vanilla modules were like many, simply seen as being in the mid-range, offering no high-performance product or unique features of any description.

However, the boom in residential installations in Germany and the emergence of utility and commercial-scale power plants in Italy had a massive impact on Yingli's mounting annual shipment levels. As a percentage of revenue, module sales in Germany accounted for over 60% of its business in 2009 and above 50% through 2011; focusing on the sweet spot of the industry proved to be an important strategy.

Sponsorship

Football is the best-attended and viewed sport in Europe and proved to be a key marketing tool for many module manufacturers, especially in Germany.

The strategy peaked with none other than Yingli Green being the major sponsor of the World Cup in South Africa in 2010. Time and time again in quarterly conference calls, Yingli's management have highlighted the importance of its branding and sponsorship. Yingli has become one of the most widely identified suppliers – in just a few years, and in an overcrowded market.

Aggressive tactics

With emphasis on Europe, and Germany in particular, another key success strategy for Yingli has been its aggressive pricing. When Germany started cutting its feed-in tariff (FiT) periodically at 15% rates, Yingli was already prepared and pre-announced to its customers that it would lower prices to retain the ROI rates that end-users had become accustomed to. More often than not it was Yingli that led the price declines ahead of its rivals, capturing orders ahead of the curve and FiT cuts. Many rivals were caught off guard or simply held out to see how FiT cuts would impact demand.

Picking winners

As the US market has picked up speed over the last few years, Yingli Green has emerged as a major supplier to that market as well. Yet instead of rushing to sign up countless distributors across the vast country, Yingli focused attention on servicing a smaller number of customers that had, or were in the process of gaining, strong market share in the best regional markets, such as California.

The best example of this is SolarCity. Yingli is its major module supplier. Recently, SolarCity said that it expects its PV installations to increase by 60% in 2013. Needless to say that Yingli seems to have picked one of the winners in the US market.

Sustainability

The difficult question is whether Yingli can now retain its new-found leadership position and perhaps carve out an even bigger slice of the market.

PV-Tech recently identified the R&D spending habits of the top ten module suppliers, which provides a key insight into the future capability of companies to remain competitive. Though a risky exercise, it was startling to see how aggressive Yingli Green has been in focusing both financial and human resources on R&D.

Also, aggressive cost reduction and pricing, as well as aggressiveness in regional market penetration and going after the downstream utility market, notably in China, has driven Yingli Green to the top of the rankings.

Other than missteps, which module supplier is going to be as aggressive as Yingli Green and end its reign?

This column is a revised version of a blog that originally appeared on PV-Tech.org.

Mark Osborne is currently the Senior News Editor for *Photovoltaics International* and PV-Tech website. He has launched multiple technology titles in print and online, covering manufacturing in the automotive, shipping, semiconductor and solar sectors, in a publishing career spanning three decades.