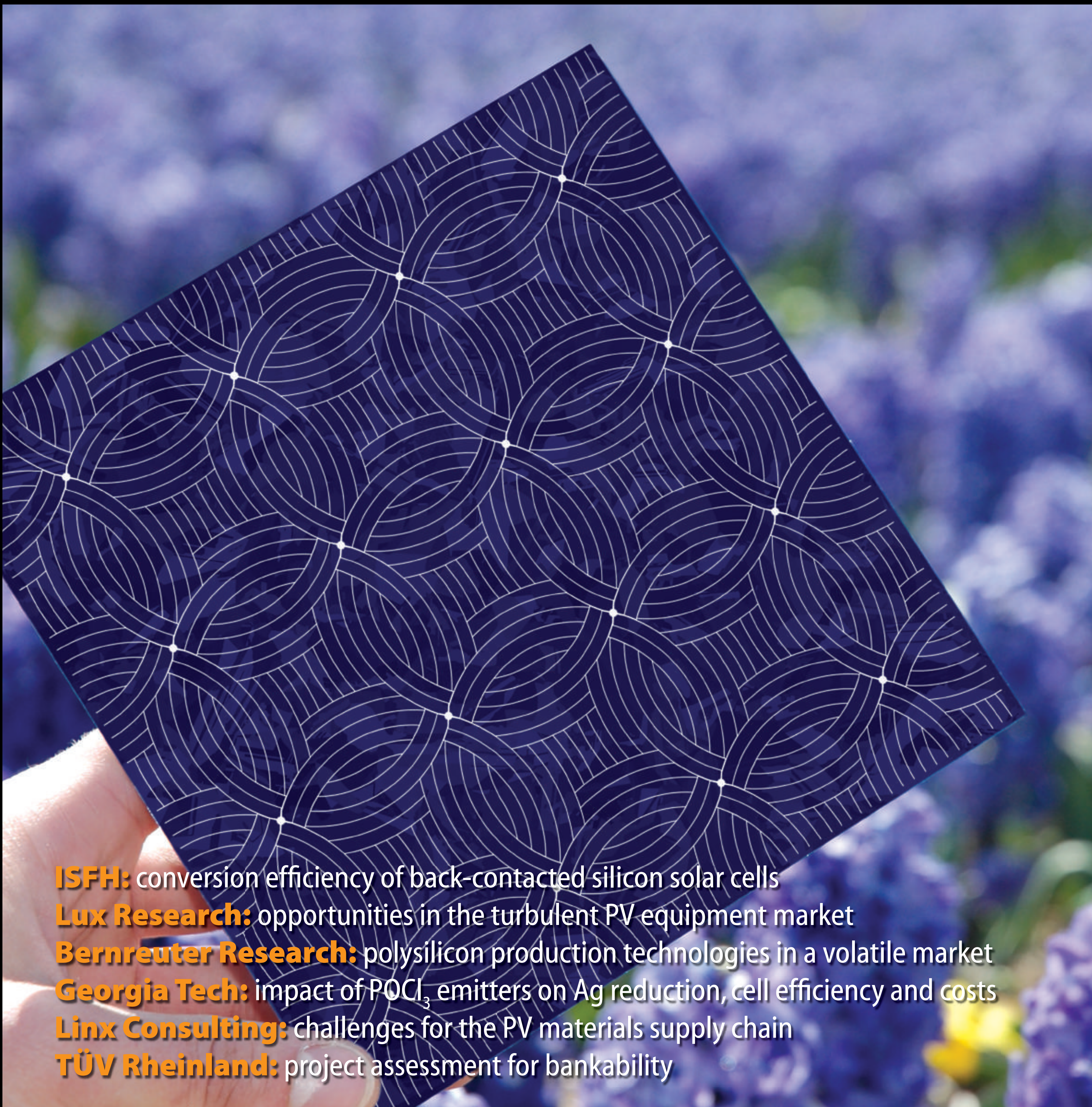
Eighteenth Edition

Photovoltaics International

THE TECHNOLOGY RESOURCE FOR PV PROFESSIONALS



ISFH: conversion efficiency of back-contacted silicon solar cells

Lux Research: opportunities in the turbulent PV equipment market

Bernreuter Research: polysilicon production technologies in a volatile market

Georgia Tech: impact of $POCl_3$ emitters on Ag reduction, cell efficiency and costs

Linx Consulting: challenges for the PV materials supply chain

TÜV Rheinland: project assessment for bankability

Fourth Quarter, November 2012

www.pv-tech.org

Photovoltaics International

Published by:
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Printed by Buxton Press
Photovoltaics International
Eighteenth Edition
Fourth Quarter 2012
Photovoltaics International is a quarterly journal published in February, May, August and November.

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

ISSN: 1757-1197

USPS Information
USPS Periodical Code: 025 313

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

Foreword

On 12 November the International Energy Agency published the 2012 World Energy Outlook, in which it said solar was the fastest growing renewable technology and that renewables would become the second largest source of power generation in the world by 2015.

Meanwhile, module and inverter prices have been steadily falling and, despite subsidy cuts, this is enabling another bumper year for solar installations globally; we predict close to 32GW will be installed in 2012. The downside is that this is based on manufacturers largely selling components at cost or in some cases less than cost in order to maintain factory utilization rates.

The next 12 months will therefore be critical as manufacturers seek to drive their process costs down to maintain growth in the end market and be able to sustainably match the current crop of factory gate prices.

Our focus here at *Photovoltaics International* has always been on efficiency improvement and driving down the cost per watt of modules. Over the next 12 months we plan to bring you more detailed technical articles on how you can reduce cost in your manufacturing process by implementing some very clever new process steps, materials and equipment.

In this issue we take a look at some of the market dynamics driving prices in the supply chain so that you can make better decisions to help reduce your overall cost per watt and increase your efficiency at the same time.

Lux Research in its quirkily entitled 'Turning Lemons into Lemonade' (p.12) sets the scene by showcasing significant opportunities for certain segments of the PV manufacturing equipment marketplace even though c-Si utilization is operating at almost 55% capacity.

Find out how much you should be paying for materials in 2013 as **Linx Consulting** (p.25) delves deeper into the bill of materials for module production costs, which for c-Si come to US$0.43/Wp and for CIGS US$0.27/Wp.

Of course costs for PV deployment are not just down to manufacturing components, materials and equipment, but also consist of end market dynamics and balance of system costs. **Mainstream Energy** (p.115) looks at ways to reduce the 'soft' costs of solar installations in the USA.

Acero Capital (p.124) seeks to bring it all together in an ambitious paper that deconstructs the solar sector by analyzing costs all along the value chain. In this issue they outline the way the value chain works, and in the second part of this article, published in the next issue, you will get to see where technology investment can still help bring down costs further.

It has been a fascinating year in 2012 and the future in 2013 looks uncertain for many players currently involved in the supply chain globally. However the underlying market dynamics and necessity for more efficient clean generators globally means that solar generated electricity is here to stay.

I look forward to working with you all through 2013,

David Owen
Publisher
Solar Media Ltd

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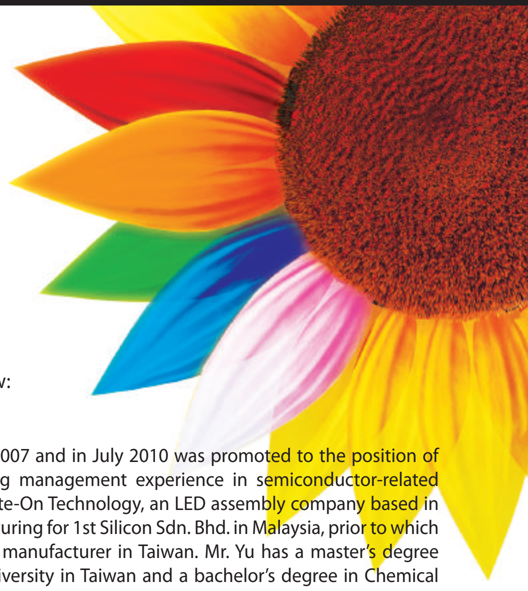
Imagine
How a single Solar Module
Can save a polar bears home
With a 240Wp solar module
It can replace 3 barrels of oil energy
Solar Energy, that reduces risks of global warming…
Supports a younger, healthier earth
We need Solar!

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:

Trinasolar

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.

SHARP

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).

MOTECH

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.

Fraunhofer ISE

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.

SUNTECH

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.

NSP NEO SOLAR POWER

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.

moserbaer Photo Voltaic

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.

Fab & Facilities

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News

Hanwha Group sets up Hanwha Q.Cells

South Korean conglomerate Hanwha Group has officially sealed the acquisition of German solar cell manufacturer Q-Cells by announcing the launch of Hanwha Q.Cells.

The establishment of Hanwha Q.Cells positions Hanwha as the third largest solar manufacturer in the world, the company claims. The launch is part of Hanwha Group's strategic investment plans, which aim to broaden the company's solar offerings and accelerate technology developments ranging from advanced cell technology to system optimization for lowering Levelized Cost of Electricity, EPC and project development capabilities.

At present, Hanwha has 2.3GW of manufacturing capacity distributed across Germany, Malaysia and China, which the company believes gives it a competitive advantage to supply any region in the world, free of trade sanctions.

The acquisition was originally announced at the end of August and includes Q-Cells' headquarters, R&D centre and administrative operations in Germany; 200MW cell and 120MW module manufacturing facilities in Germany; an 800MW cell manufacturing facility in Malaysia; entities in the US, Australia and Japan; 34 patents; and 1,225 employees.

Hanwha Group has officially sealed the acquisition of German solar cell manufacturer Q-Cells.

Capacity News Focus

Production and staff cut at Suntech's module assembly plant in Arizona

A single shift will operate Suntech Power Holdings' only module assembly plant in the US following the loss of around 50 jobs.

Production at its assembly plant in Goodyear, Arizona will be reduced from an annual module capacity of 45MW to only 15MW as the company continues to restructure its manufacturing operations and combat industry overcapacity.

The company also claimed that the move was in response to higher production costs as a result of recent import tariffs imposed on solar cells imported into the US from China, for which Suntech had been given a 35.97% penalty.

Panasonic pulls Malaysian PV production plant expansions

Mounting losses expected to top ¥765 billion (US$9.6 billion) and a dash to cut costs across all operations has led to Panasonic halting further capital expenditure and expansion plans indefinitely at its new PV module plant in Malaysia.

Releasing its Q2 2013 financial results, Panasonic confirmed that it expected a significant fall in demand for its HIT modules in the second half of the year, primarily due to weakening demand across Europe.

Emphasis on restructuring its solar operations were said to be focused on the Japanese residential market, while the company is integrating R&D, production and sales operations within its Eco Solutions segment. Panasonic includes lighting and environmental systems within its Eco Solutions segment.

Source: Suntech

Production at Suntech's assembly plant in Arizona will be reduced from an annual module capacity of 45MW to only 15MW.

Indonesia's LEN Industri and Pertamina partner to build 60MW PV production plant

Indonesian state-owned companies LEN Industri and Pertamina have joined forces to build a 60MW solar cell production plant in Bandung, the capital of West Java province.

A presidential regulation issued in 2006 said solar energy should account for between 0.2% and 0.3% of the country's national energy usage by 2025, or the equivalent of 1,000MWh.

ReneSola establishes regional sales headquarters in Singapore

PV modules and wafers manufacturer ReneSola has announced the establishment of its Asia Pacific, Middle

Source: Renesola

ReneSola has announced the establishment of its Asia Pacific, Middle East and Africa regional sales headquarters.

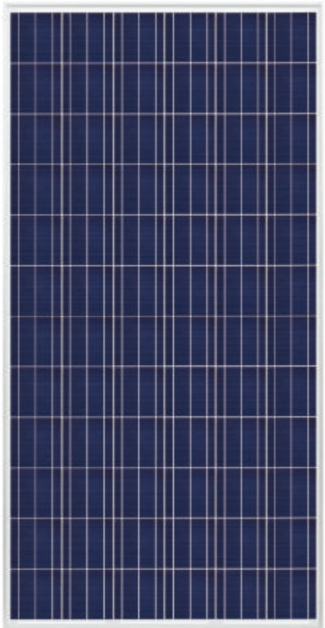
East and Africa regional sales headquarters in Singapore.

The company said ReneSola Singapore would help strengthen its business in Asia Pacific, the Middle East and Africa, while taking advantage of Singapore's strength as a financial and talent hub in Southeast Asia.

Trina formally opens APMEA headquarters

Trina Solar's new Asia Pacific, Middle East and Africa (APMEA) headquarters in Singapore has been put into formal operation, the company has announced.

The company's CEO Jifan Gao said the formal opening of its APMEA headquarters would strengthen its presence in these emerging solar markets.



Source: Trina Solar

Trina Solar's new Asia Pacific, Middle East and Africa (APMEA) headquarters in Singapore has been put into formal operation.

Trina Solar's new headquarters will provide management functions covering administration, sales, project development, R&D, logistics and purchasing operations. The administrative regions include Singapore, Thailand, Malaysia, the Philippines, India, Japan, Australia, New Zealand, Korea, the Middle East and Africa.

Hyundai's US$20.8 million solar research centre operational

An investment of US$20.8 million has allowed Hyundai Heavy Industries (HHI) to complete its new Solar R&D Center in Eumseong, Korea, home to its 600MW of cell and module manufacturing operations.

The company said that it had recently completed the development of copper-contact selective emitter solar cells with 19.7% conversion efficiency as well as a passivated emitter, rear locally-diffused (PERL) cells with 20.4% conversion efficiency. The company said that both technologies have been verified by Fraunhofer ISE.

TerniEnergia establishes South African subsidiary

Italian renewable energy specialist and PV systems integrator TerniEnergia has announced the establishment of a subsidiary in Cape Town, South Africa.

TerniEnergia South Africa will be 100% owned by TerniEnergia, and its establishment is in line with the company's international development strategy, which has also seen the establishment of a

Polish arm and a Greek office. The South African subsidiary will carry out all the firm's activities in South Africa and neighbouring countries.

TerniEnergia South Africa has already been selected as the EPC provider for the first phase of the construction of a 9.5MWp PV plant at the Upington airport in the Northern Cape of South Africa. The project is scheduled to connect to the grid by the end of October 2013.

SPG Solar relocates to Petaluma, California

Solar power products and services provider SPG Solar has announced it will be relocating its corporate headquarters to Petaluma, California, effective January 1, 2013.

Source: SPG Solar

SPG Solar has announced it will be relocating its corporate headquarters to Petaluma, California, effective January 1, 2013.

The new 7,747 square-metre complex will include a research and development facility comprising two testing labs, one for racking and the other for electrical and communications. In addition, the company said its headquarters will include reliability facilities, which will incorporate a prototype facility and a destructive test facility, as well as a customer centre that will house an interactive and operational product showcase.

Yingli to open Zurich HQ

China's Yingli Green Energy has announced plans to open a European regional headquarters in Zurich, Switzerland.

The manufacturer of Yingli Solar products said the move was intended to centralize its operations in Europe.

LDK Sells Solar Plants to Henan Xindaxin for US$22 million

LDK Solar, one of the world's largest producers of solar wafers, has finalised a deal to sell three solar plants to Henan Xindaxin Materials for RMB140 million (US$22.4 million).

The agreement, which was announced in October, is part of LDK's effort to claw its way out of a US$3.6 billion debt.

PV-Tech understands that LDK will lease back the plants at its manufacturing sites from Xindaxin for RMB9.9 million a year for six years, starting on 1 November. Kaifeng, the China-based chemicals company, also retains the right to repurchase them at a later date.

According to data compiled by Bloomberg, LDK was US$3.6 billion in debt at the end of the second quarter and analysts expect it to lose US$440 million this year.

Work to begin on new SolarMax HQ

US installer SolarMax has announced plans to begin work on its new headquarters in Riverside, California, with the incorporation of a solar roof into a refurbished historic warehouse building.

The move is expected to create 1,600 jobs directly and indirectly, the company said.

SolarMax has also announced that it will establish a US$200,000 Endowed Graduate Fellowship Fund for the University of California Riverside, which is also located on the site.

The company plans to occupy the 15,300 square metre building by the end of the year.

ATMI announces plans for new manufacturing facility in South Korea

ATMI is expanding its focus in the Asia-Pacific microelectronics market, specifically for its South Korean customers. The company, which is known to work closely with Applied Materials ion implant divisions, is building an 118,000 square foot manufacturing facility in the JangAn, Gyeonggi province.

The company celebrated its announcement with a ground-breaking ceremony held at the site, which is expected to be ready for high-volume production in the second half of 2013. The facility will manufacture a range of products for customers in the semiconductor market including SDS and VAC gas delivery systems and materials for use in semiconductor and solar ion implant applications.

Other News

Tenesol to slash workforce in France

French BIPV specialist Tenesol is to lay off 70 of its employees in France.

The move is said to be part of recently announced restructuring plans by Tenesol's parent company SunPower, which will involve reducing its workforce by 900 employees.

But French trade union Federation Chimie Energy (FCE) Cfdt has revealed that Tenesol will also be affected and lose up to 70 French workers.

In a statement, the FCE Cfdt called for Total, which owns the majority of SunPower, to make a u-turn on its decision despite the competition that Tenesol faces from China.

SunPower to streamline Philippines Fab 2 manufacturing plant

SunPower has announced plans to restructure its Fab 2 cell manufacturing plant in the Philippines. The company's Fab 1 facility was shuttered in April this year with some equipment transferred from there to Fab 2, to reduce manufacturing constraints during the second quarter.

Source: SunPower

SunPower has announced plans to restructure its Fab 2 cell manufacturing plant in the Philippines.

SunPower is expected to temporarily idle six of the 12 lines in its Fab 2 plant and 20% of panel manufacturing in the Philippines to significantly reduce inventory, lower operational costs and improve efficiency. As a result, the company expects the overall blended utilization for the fourth quarter to be approximately 60%. Additionally, the company will reduce its workforce by approximately 900 employees with the reductions occurring primarily in the Philippines.

Solar Frontier's Kunitomi production plant receives ISO 14001 and OHSAS 18001 certifications

Solar Frontier's Kunitomi solar panel production plant recently received ISO 14001 and OHSAS 18001 certifications. Both certifications are essential for Italian PV projects to be eligible for the country's feed-in tariff, while other countries such as the UK, France and Mexico are also considering such requirements.

The ISO 14001 certification is designed to provide an assurance that the company's environmental impact is being measured and improved, which can ultimately lead to a reduction in the cost of waste management, lower the distribution costs and savings in consumption of energy and materials. OHSAS 18001 is a British standard for occupational health and safety management systems. Its aim is to help organizations cut risks to employees and put the right health and safety measurements in place.

Giga Solar Materials plans increased PV paste output at Taiwanese plant

Giga Solar Materials, a Taiwanese specialist in the development of conductive paste for solar cells, is reportedly planning to increase output at its photovoltaic conductive paste plant in the Southern Taiwan Science Park in order to meet demand from PV equipment manufacturers.

According to industry executives reported by Taiwan Economic News, the company has become the first Taiwanese PV manufacturer to boost production during "this round of business cycle upturn".

SoloPower officially opens roll-to-roll flexible CIGS thin-film plant

Already incorrectly type-cast by the mainstream media as the illegitimate love child of failed copper indium gallium di selenide (CIGS) thin-film manufacturer, Solyndra, flexible CIGS thin-film start-up SoloPower has officially opened its first volume production plant in Portland, Oregon. Unlike other CIGS start-ups, SoloPower uses proprietary roll-to-roll processes via electro-deposition processing as its differentiator.

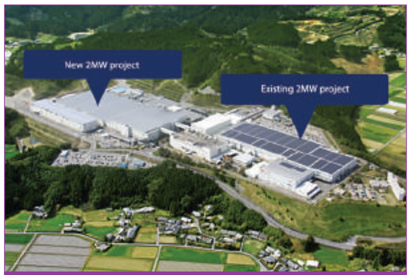
Heraeus opens Taiwanese PV manufacturing facility

The Heraeus Photovoltaics business unit, part of German technology firm Heraeus, has opened a new manufacturing facility in Taiwan demonstrating its commitment to the PV industry in the country and region.

The facility, which will allow the PV unit to provide a faster service and customized products for the Taiwanese market, features a large laboratory as well as manufacturing capabilities. The company has also hired and trained local personnel to operate the facility.

Solar Frontier to suspend production at its Miyazaki-Daini plant

Japanese thin-film module supplier Solar Frontier is planning to close the doors of its 60MW Miyazaki-Daini PV module manufacturing facility in south-west Japan for an indefinite period of time in order to focus on increasing output at its larger Kunitomi plant, Reuters has revealed.



Source: Solar Frontier

Solar Frontier is planning to close the doors of its 60MW Miyazaki-Daini PV module manufacturing facility.

Citing a company spokesman, Reuters reported that Solar Frontier will be able to boost production of PV modules by 50% in 2013, from 600MW to 900MW, if more efforts were placed on production at the Kunitomo plant in southern Japan. This move will help to meet the growing demand in Japan.

Solar Frontier had a total of three manufacturing plants in Japan but closed one of them in 2010. By closing the Miyazaki-Daini plant, the company will be able to place its entire efforts on the Kunitomo plant which began operating in February 2011. The Miyazaki-Daini plant is due to shut-down in December.

Turning lemons into lemonade: Opportunities in the turbulent PV equipment market

Fatima Toor, Lux Research Inc. Boston, Massachusetts, USA

ABSTRACT
Production equipment is the backbone of the PV industry, but the equipment sector is suffering because of overcapacity. The 2012 global capacity utilization is at 55% for crystalline silicon (x-Si) module production, 70% for cadmium telluride (CdTe) and 80% for copper indium gallium (di)selenide (CIGS). Under these market conditions, there are almost no expected capacity expansions in the near term. The overcapacity has driven the average selling price (ASP) for modules significantly lower, resulting in hyper-competition in the PV industry, where almost all PV companies recognize the importance of product differentiation while still reducing costs. These market conditions present an opportunity for equipment manufacturers to differentiate their offerings through enabling lower production costs and higher efficiency of cells and modules.

Geographical distribution of equipment manufacturers

Lux Research surveyed, via primary and secondary research, 493 PV equipment manufacturers for various PV technologies and value chains in order to analyze global trends; it was found that 28% of PV equipment manufacturers are based in China, while 20% are based in Germany (see Fig. 1). It is important to note that, to date, the revenues of German and US equipment manufacturers have been ahead of their Chinese counterparts. This trend, however, might be changing. From conversations with equipment manufacturers, it was ascertained that the number of Chinese equipment manufacturers is growing; some of these simply replicate equipment designs, while others introduce their own and are engineering to current equipment designs to compete with Western equipment manufacturers. The Chinese will be able to sell cheap equipment, which stiffens the competition for Western equipment manufacturers. The latter will therefore need to reduce equipment costs while differentiating. Overall, there are short-term sales opportunities for equipment manufacturers when cell and module manufacturers try to differentiate their products and long-term opportunities as global solar capacity grows in dominant and emerging geographies.

> "To date, the revenues of German and US equipment manufacturers have been ahead of their Chinese counterparts."

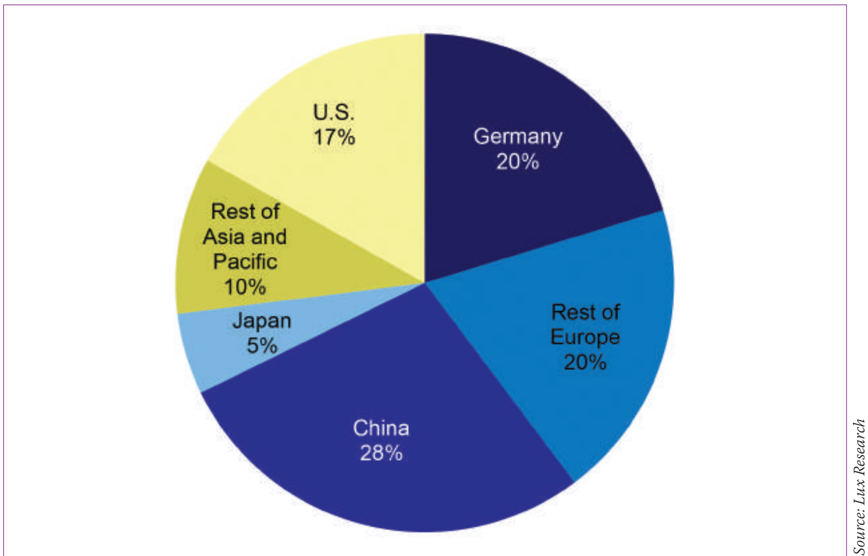
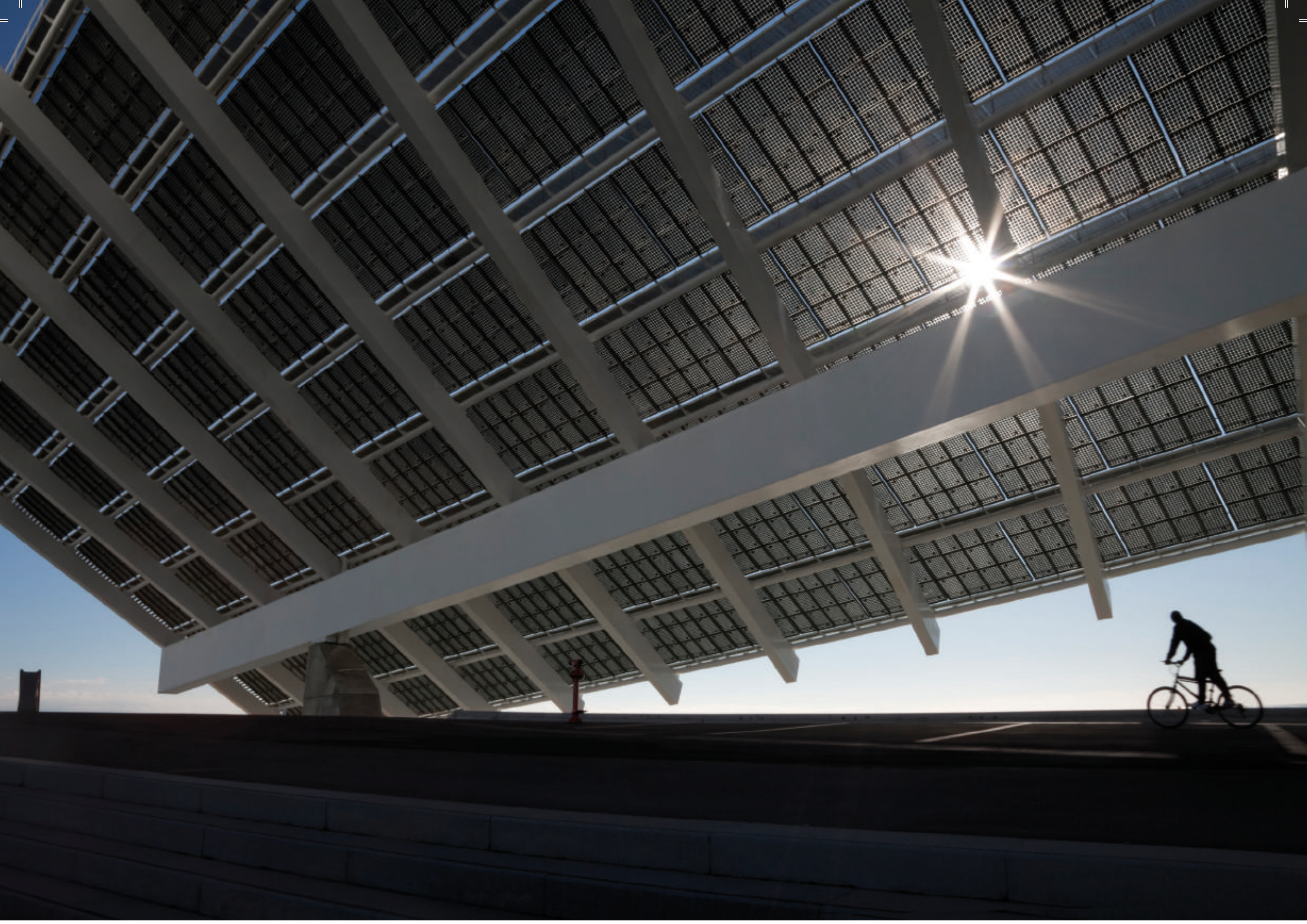


Figure 1. Geographical distribution of 493 surveyed PV equipment manufacturers, with Asia/Pacific comprising 43%.

Room for improvement in PV manufacturing processes

The drive by the PV module producers to reduce production costs and increase efficiencies provides an opportunity for equipment manufacturers. Existing production processes across the existing PV technologies – x-Si, CIGS and CdTe – are non-optimum and there is room for significant improvement. Some of the opportunities for each technology segment are:

- Monocrystalline silicon (c-Si) ingot growth using Czochralski (Cz) pullers is too costly, too much silicon is wasted in wafer sawing, standard cell designs lose 10% to 12% of absolute efficiency from their highest efficiency potential, and module manufacturing remains unnecessarily labour intensive. The opportunity for improvement is glaringly obvious in terms of manufacturing processes and equipment to improve cell efficiencies and reduce production costs.
- CIGS and CdTe thin-film technologies rely on custom equipment because of the importance of process parameters for each individual process step. The two largest cost contributors in CIGS and CdTe production are equipment and materials costs. While CIGS and CdTe producers are aiming for high module efficiencies to maintain competition with current x-Si technologies, there is a need for reduction in capital equipment and materials costs.
- Idle capacity within PV companies allows them to upgrade polysilicon,



ingot, wafer, cell and module lines, assuming appropriate cash balances. These upgrades will enable long-term survival of the key PV industry manufacturers, since they will be able to differentiate their products from standard offerings. Those who sit idle while their equipment idles are sealing their fate.

Requirement for new equipment to drive down production costs

There are opportunities across the entire PV value chain for optimizing production processes to reduce manufacturing costs and improve cell and module efficiencies. Fig. 2 shows a snapshot of some innovative technologies across the PV value chain that will not only enable differentiation for the PV manufacturers but also provide opportunities for equipment manufacturers. This should not be taken as a comprehensive list: Lux Research's report [1] covers many other examples of innovative technologies in addition to the ones included in Fig. 2. Each of the innovative technology areas in Fig. 2, along with the corresponding equipment opportunities they offer, will be discussed next.

"There are opportunities across the entire PV value chain for optimizing production processes to reduce manufacturing costs and improve cell and module efficiencies."

Fluidized bed reactor (FBR) polysilicon growth

According to the Lux Research Solar Supply Tracker [2], Siemens is the most popular industry process for polysilicon production, maintaining 88% of the market share; the fluidized bed reactor (FBR) maintains 6% of the market, and the rest are various UMG-Si processes. The FBR process uses only one-sixth of the energy required by the Siemens process, but current process complexity prevents it from becoming mainstream. Two major polysilicon manufacturers, MEMC and REC, use the FBR process for polysilicon production; recently GCL-Poly, the world's number one polysilicon manufacturer in terms of capacity, announced it was developing FBR technology to reduce production costs.

Three key advantages of FBR over the Siemens process are: 1) a lower energy requirement of 10kWh/kg because of a low-temperature (800°C) process; 2) continuous processing instead of batch processing as in the Siemens process; and 3) higher material yields than Siemens. The end product is polysilicon granules with a 1mm diameter, which can be packed more densely in an ingot crucible than the polysilicon chunks produced by the Siemens process.

Even with these advantages, FBR remains uncommon. There are several reasons for FBR's small market share: most notably no off-the-shelf FBR reactors are available and it suffers from process complexity in that the Si granules can be easily polluted by impurities. There is therefore an opportunity for equipment manufacturers to develop off-the-shelf FBR equipment that will enable reduced production costs for polysilicon.

Quasi-monocrystalline silicon (qc-Si) ingot growth

During recent visits to solar conferences, Lux Research observed that numerous leading wafer, cell and module manufacturers are using quasi-monocrystalline (qc-Si) wafers. The advantage of qc-Si ingots is that, with a small retrofit change to existing directional solidification (DS) furnaces, ingot manufacturers can produce wafers with a performance closer to that obtained by conventional Cz c-Si wafers but at a cost similar to that for mc-Si wafers.

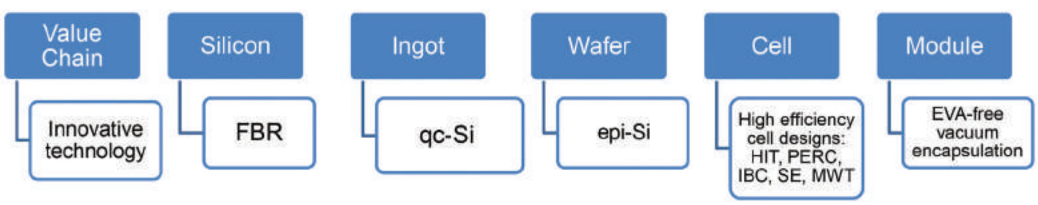
In qc-Si ingot growth, c-Si seed is used for the ingot-casting process to obtain c-Si and mc-Si material consecutively. The qc-Si ingot growth process uses DS furnaces. However, a c-Si seed plate is used at the bottom of the crucible, and then the molten silicon poured into the crucible is directionally solidified with tight temperature control. The seed plate has several crystal grains on the edges, while the centre is formed of a single crystal: this occurs because it is difficult to control the temperature profile on the edges of the crucible.

The resulting ingot has mc-Si material on the edges of the ingot, while the majority of the ingot is c-Si. An advantage of this ingot growth is also that the c-Si wafers obtained from the centre of the ingot are square instead of pseudo-square, as in the traditional mono process, which typically yields a wafer with rounded corners, resulting in reduced active area in the module. According to the Lux Research cost model, qc-Si ingot growth results in around \$0.10/W cost saving relative to Cz c-Si growth.

Because of all these factors, ingot and wafer manufacturers are already upgrading their existing DS furnaces used for mc-Si growth to switch to qc-Si ingot growth that enables high-quality silicon and square c-Si wafers at a fraction of the cost of Cz c-Si wafers. GT Solar and AMG Idealcast are ahead of the game, in offering qc-Si ingot growth furnaces to their customers. Other equipment manufacturers will follow, creating more sourcing options for ingot manufacturers, while placing the onus on the equipment providers to compete in price or differentiate in mono-to-multicrystalline yield ratios.

Epitaxial silicon (epi-Si) wafers and cells

Epi-Si, which is thin crystalline silicon, is becoming an increasingly popular technology: several start-ups are working on various different types of epi-Si, including epi-Si on substrates and epi-Si growth and peel. One start-up that stands out is Solexel, who recently announced a 156mm × 156mm, 20.6%-efficient cell based on its epi-Si growth-and-peel technology. Epi-Si reduces the Si costs significantly but has high capex requirements. However, it is important to note that Solexel integrates the back-contact cell design processing before the substrate attachment and then peels off the entire cell structure; this results in an overall cost saving for wafer and cell manufacturing. Solexel plans to enter the market with a 20% module efficiency by 2014, with manufacturing cost at the \$0.42/W level.



Source: Lux Research

Figure 2. Example innovations across the entire PV value chain providing opportunities for equipment manufacturers.


ONTARIO
CANADA

Epi-Si techniques use a combination of standard and custom equipment, which presents an opportunity for equipment manufacturers who would like to develop differentiated equipment.

High-efficiency crystalline silicon cell designs

Standard crystalline silicon (x-Si) cells are sub-optimal in terms of their design, because they suffer from shading losses due to the front metallization, and recombination losses in the bulk, front and back surfaces of the x-Si cell. These effects result in almost 10–12% absolute efficiency loss (assuming an x-Si efficiency potential of 27–29%). Given the significant room for improvement, several companies are working on improving cell efficiencies using various designs that reduce shading and recombination losses. These cell designs include heterojunction with intrinsic (HIT), passivated-emitter rear cell (PERC), selective emitter (SE), interdigitated back contact (IBC) and metal wrap-through (MWT). All of these designs offer an opportunity for equipment manufacturers to develop equipment that enables high performance, but at the same time a reduction in cost.

Some companies already have a lead in providing equipment for manufacturing high-efficiency cell designs, including Meyer Burger and Applied Materials, and others are following suit. Among cell designs that will see growth in their market share will be PERC, HIT and SE because these do not require different module packaging from that for standard cells. Equipment manufacturers should therefore target their equipment offerings to facilitate the implementation of these cell designs. Most of the designs require upgrades to existing production lines, presenting a short-term revenue-generating opportunity for equipment manufacturers.

EVA-free vacuum encapsulation of PV modules

In PV technology it is not just about the \$/W but also the \$/kWh: in other words, module cost and lifetime are both critical. The most common encapsulant in module packaging is ethylene vinyl acetate (EVA), which is known to yellow over time and decompose to acetic acid, causing corrosion of metal contacts and an overall reduction in module performance. EVA-free vacuum encapsulation can eliminate these issues and prolong the life of modules.

Apollon Solar is one equipment manufacturer developing an EVA-free vacuum encapsulation technology, dubbed 'new industrial solar cell encapsulation,' or NICE. Traditional modules encapsulate the cells between two layers of EVA, which is then protected by the front glass and a backsheet. Taking advantage of technology used by insulating glass manufacturers, Apollon Solar vacuum-seals the cells between two sheets of glass using a sealing process requiring 120°C of localized heat. A thermoplastic spacer (TPS) is placed between the sheets of glass to hermetically seal the module and keep the glass sheets from crushing the cells; the TPS is placed only along the edges of the module and also acts as an edge sealant.

The resulting modules have passed International Electrotechnical Commission (IEC) environmental and degradation tests, and further testing has been carried out to prove that these modules are more robust than traditional modules. Apollon Solar claims cost-of-ownership savings between \$0.13/W and \$0.16/W. Innovative module packaging technologies, which reduce costs while improving module lifetimes, therefore provide an opportunity for equipment manufacturers.

Near- and long-term outlook for PV equipment industry

The overcapacity in the PV industry has reduced utilization to an all-time low. Contrary to the general consensus, idle capacity is an opportunity in the near and long term for PV manufacturers to upgrade to high-performance products, assuming that funding is available. The current low capacity utilization in the PV industry should and will trigger equipment upgrades across the entire value chain, starting from high-purity polysilicon production upgrades to upgrades for high-efficiency cell and module designs. These upgrades will grow demand for differentiated PV equipment, enabling the long-term survival of innovative PV industry manufacturers and the equipment providers that help them to do so.

"Idle capacity is an opportunity in the near and long term for PV manufacturers to upgrade to high-performance products."

Moreover, while there may be tremendous overcapacity in China, as PV demand grows in emerging markets such as India, South America and the Middle East, PV equipment manufacturers will sell equipment to these markets to an increasing extent. Equipment manufacturers' business development operations should look to these geographies now while their sales teams should renew their passports or start scouting for local talent to position for growth.

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About the Author

Fatima Toor is an analyst at Lux Research and leads the Solar Components Intelligence Service. Along with her team she helps clients – Innovation 1000 corporations, leading institutional investors, utilities and public policy makers – make better strategic decisions and monitor the ever-changing global solar market. Prior to joining Lux Research, she was a postdoctoral researcher in the Silicon Materials and Devices group at the National Renewable Energy Lab (NREL). Fatima obtained her Ph.D. and M.A. in electrical engineering from Princeton University.

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Materials

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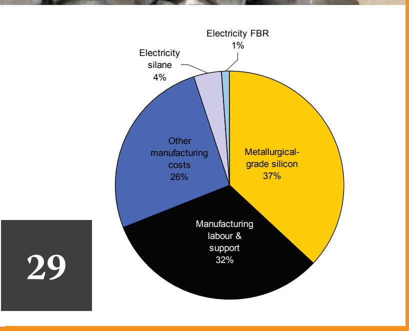


Electricity FBR
1%
Electricity silane
4%
Other manufacturing costs
26%
Metallurgical-grade silicon
37%
Manufacturing labour & support
32%
29

Solarbuzz predicts polysilicon capacity to grow 22% in 2012

Analyst NPD Solarbuzz is predicting that polysilicon capacity will grow 22% in 2012 and another 18% in 2013.

According to its latest **Polysilicon and Wafer Supply Chain** Quarterly Report for Q3 2012, the industry's polysilicon processes for PV applications are anticipated to drop 52% this year while plant utilization will decline from to 63%, from 77% in 2011. Total polysilicon capacity will be in excess of 385,000 tons this year, of which 70% will be held by a small group of tier 1 producers.

Solarbuzz noted that under its most-likely end-market scenario over the next few years, tier 1 providers are expected to satisfy all polysilicon demand. Further, unless end-market demand delivers an unexpected surprise to the expected polysilicon requirements, many of the 57 tier 2 and 3 producers will leave the industry within the next year and a half. Further, it's predicted that even a few of the less-experienced tier 1 makers may not make it over the next two years.

NPD Solarbuzz is predicting that polysilicon capacity will grow 22% in 2012

PVA TePla Solar Systems division sales only €6.6 million in nine months

Silicon crystallisation equipment supplier PVA TePla generated revenue of €83.7 (US$106.3 million) in the first nine months of 2012, slightly higher than the same period a year ago when revenue reached €77.3 million.

Having a diversified business helped soften the blow from the acute overcapacity in the PV industry. Sales within its Solar Systems division were only €6.6 million for the first nine months, down from €10.1 million in the same period of 2011. Operating earnings (EBIT) amounted to €6.2 million.

However, order intake this year within its Solar Systems division has amounted to only €1 million. Overall order intake from all segments (€42.2 million) has fallen to a book-to-bill ratio of 0.4, down significantly from a book-to-bill of 1.7 in the previous year period.

GT Advanced Technologies places big bet on ultra-thin wafers

GT Advanced Technologies (GTAT) has acquired ultra-thin wafer equipment start-up, Twin Creeks Technologies for US$10 million.

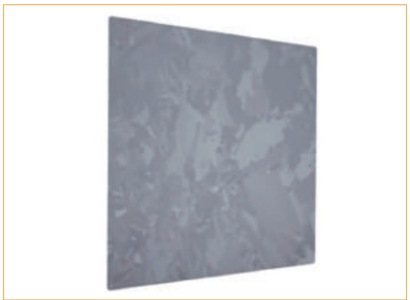
GTAT believes that Twin Creeks proton induced exfoliation technology has a multitude of applications in the future, including ultra-thin silicon wafers, silicon carbide, sapphire, germanium as well as other crystalline-based material substrates that could benefit from being much thinner and therefore less costly in the future.

Twin Creeks only came out of stealth mode in March 2012 when it announced its Hyperion 3, a commercial wafer production system. The deal to acquire the company was said to have been undertaken with Twin Creeks investors. The deal will also include future royalty payments to the investors based on future sales.

GTAT said that included in the acquisition was a portfolio of approximately 30 granted US patents and over 70 pending US and international patent applications.

LDK Solar to receive US$37 million compensation from wafer supply deal cancellation

Long-term solar wafer supply agreements continue to be cast into the history books as an unidentified European-based PV manufacturer terminated a contract with supplier LDK Solar.



Source: LDK Solar

An unidentified European-based PV manufacturer has terminated a contract with supplier LDK Solar.

The cancellation agreement will result in LDK Solar receiving approximately US$37 million in much needed compensation as the company struggles with massive debts.

SiC unable to meet payment obligations

SiC Processing has finalised a last minute deal to delay payments to major creditors until 28 February 2013.

The company said the move was prompted by volume and price declinations, incomplete liabilities from its expansion programme of the past two years and a parent guarantee for a rental contract with insolvent REC Wafer Norway.

The creditors, which include the Norwegian landlord of SiC Processing, a supplier of SiC recycling lines and a shareholder of SiC Processing, agreed to delay the company's outstanding debt until 28 February 2013.

Source: GTAT

GTAT has acquired ultra-thin wafer equipment start-up, Twin Creeks Technologies.

GT Advanced Technologies settles trade secrets case against Poly Plant Equipment

GT Advanced Technologies has announced the settlement of a pending lawsuit against a Poly Plant Equipment employee, Fabrizio Goi, and PPP Equipment Corp.

The lawsuit was over the misappropriation of GTAT's trade secrets that were related to its polysilicon reactor equipment technology.

The company did not provide further details.

Access to credit hitting GT Advanced Technologies PV customers

GT Advanced Technologies has reported Q3 2012 revenue of US$110 million, down from US$167.3 million in Q2. PV business remained very weak, impacting sales.

Polysilicon equipment and service sales accounted for around 85% of total revenue (US$96 million) in the quarter. In contrast, sales of GTATs DSS furnace products, used in the production of multicrystalline ingots, were only US$2 million, compared to a peak of US$240 million in late 2010.

GT Advanced Technologies touts FBR polysilicon cost reduction breakthrough

Specialist equipment supplier GT Advanced Technologies (GTAT) is claiming its new hydrochlorination solution for trichlorosilane production used in fluid bed reactor (FBR) polysilicon production takes production costs below US$14/kg.

Polysilicon prices have been declining sharply for several years due to overcapacity and weaker than expected demand, which is driving the need to find innovative ways to reduce polysilicon production costs for the key technologies used (Siemens process and FBR) to make the material.

News

Source: centrotherm

centrotherm photovoltaics has submitted its reorganization plans to the insolvency court in Ulm.

GTAT said that the new hydrochlorination solution was designed for high-volume applications (10,000 tonnes per annum), and would provide a 20% reduction in the cost of ownership.

However, GTAT also claims that its next generation hydrochlorination heater technology further reduces production costs by increasing conversion in the hydrochlorination FBR step from 27% to 30%.

When combined with its 'SDR 600' reactor capable of producing over 600 tonnes of polysilicon annually, a polysilicon cash cost of US$14/kg can be achieved.

Polysilicon market issues continue to dog Dow Corning

Oversupply and industry uncertainty continue to affect the polysilicon market, according to supplier Dow Corning as it posted group sales of US$1.55 billion, 7% lower than last year's third quarter.

Source: Dow Corning

Dow Corning noted that polysilicon oversupply was a major issue.

As with previous quarterly management commentary, Dow Corning noted that polysilicon oversupply was a major issue. However, the company also noted that market problems would persist "well into 2013", having previously stated that overcapacity would continue throughout 2012.

Dow Corning reported sales of US$4.64 billion and net income of US$288 million for the first nine months of 2012, down 5% compared to 2011, while net income was down 47% due to falling prices and higher raw material costs.

Ferro looking at disposal of conductive pastes business

The lack of customer adoption and overall weak demand due to industry overcapacity has forced materials specialist Ferro Corporation to explore strategic options for solar pastes business.

Ferro has introduced over 20 new conductive paste-based products for the solar sector in the last 18 months, but as a result of the poor business environment in the PV sector, Ferro revised down its earnings guidance proposing to take an impairment charge of between US$175 million to US$200 million in its financial third quarter of 2012.

GT Advanced Technologies to reduce workforce by 25%

GT Advanced Technologies (GTAT) is to undergo a major restructuring of its operations in response to poor market conditions for PV manufacturing equipment.

One of the largest equipment suppliers to the PV industry said that it would be streamlining its worldwide operations to reduce costs, which included workforce reduction of approximately 25% and would consolidate existing business units into a single Crystal Growth Systems (CGS) group.

GTAT also said that revenue for the Q3 2012 would be at the low end of its previously stated guidance, of between US$110 million - US$140 million. The company will report third quarter results next week.

centrotherm photovoltaics waits for court and creditor approval on reorganization plan

Major PV equipment supplier centrotherm photovoltaics has submitted its reorganization plans to the insolvency court in Ulm, Germany.

Although the company did not provide details on what those plans would be, the company said in a statement that it had now entered a critical phase in its insolvency proceedings that also need creditor approval. Both its subsidiaries centrotherm thermal solutions and centrotherm SiTec have also filed plans with the court separately.

The company also announced a major shake-up of its management team last week as part of the planned reorganization.

3M to acquire Ceradyne under new definitive agreement

3M and Ceradyne reached an agreement, which will see 3M buy Ceradyne for US$35 per share.

The transaction holds an aggregate value of nearly US$860 million, or US$670 million net of cash, cash equivalents, short-term investments and debt acquired.

Ceradyne, a major producer of crucibles used in the production of polysilicon chunks for multicrystalline ingots and then wafers, will join the 3M Energy Advanced Materials Division.

3M noted that the agreement with Ceradyne holds an arrangement for a subsidiary of 3M to start a tender offer to purchase all outstanding shares of Ceradyne within 10 business days. The companies advised that Ceradyne's board has collectively recommended that the stockholders of the company accept the offer, which is anticipated to close during Q4 2012.

Cookson to close an ingot crucible production plant in China on weak demand

Overcapacity in the c-Si ingot/wafer supply chain has forced materials specialist, Cookson to close one of its two ingot crucible production plants in China, with immediate effect.

The company closed a similar plant in the Czech Republic in July 2012, which supplied crucibles primarily to the European market. Major European-based ingot/wafer producers such as PV Crystalox are down below 30% capacity utilization on the back of weak demand.

Source: Cookson

Cookson has been forced to close one of its two ingot crucible production plants in China.

Cookson said that the closure of one of the crucible production plants would result in a non-cash charge of £16 million, together with cash-related restructuring costs of £1 million. Cookson also said it would be reducing temporary worker levels and overtime, as well as a hiring freeze and curtailment of discretionary costs.

Other News

LDK Solar sued for overdue loans

Wafer manufacturer LDK Solar has been sued by Shanghai Rural Commercial Bank for overdue loans worth 100 million yuan (US$16 million), reports the Economic Information Daily.

Unable to resolve the dispute at a court hearing on 21 November, the bank refused to extend loan repayments.

Taiwanese conductive paste market with a 90% share

The price of Giga Solar Materials' front-side paste, back-side paste and aluminum paste are said to be 20% lower than those offered by its competitors, which has led to an increase in demand for its products.

5N Plus announces Asian expansion with new Malaysian recycling facility

Specialty metal and chemical products producer 5N Plus has opened a new recycling facility within the Kulim High Technology Park in Malaysia, completed under budget.

Product Reviews

RENA

RENA's diamond wire block saw improves wafer quality and throughput

Product Outline: The RENA RS 690-DW was developed to achieve diamond wire sawing with the highest wafer quality at the lowest cost of ownership. Depending on process parameters, a claimed throughput greater than 15MW per annum can be realised.

Problem: With wafer cost reductions under continued focus, one solution is the adoption of diamond wire sawing, which supports reduced kerf loss as well as the potential for thinner wafers. However, to reach the maximum productivity, improvements such as wafer quality and yield are required, while an important factor in the cost of ownership calculation are the coolant costs.

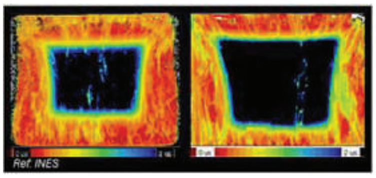
Solution: Based on experience with the RS 690-2 wire saw system, RENA engineered the new RS 690-DW especially for diamond wire applications. The mechanical results are a one-position saw with optimized wire guide axis distance, a new wire management system and a special coolant distribution system with a small footprint. The process results are claimed to provide the highest wafer quality, improved TTV values, wire consumption of <1m/wafer and a throughput greater than 15MW a year. The machine is capable of cutting 156mm x 156mm wafers with a minimum wire core diameter of 100μm. In collaboration with SH+E GROUP, RENA developed a coolant recycling system that improved the coolant lifetime and reduce process costs.

Applications: Multi- and monocrystalline Si-block sawing.

Platform: The complete wire saw with electrical cabinet is placed on a footprint of only 3,701 x 2,000 mm, resulting in a saw platform with one 680mm cutting position on the smallest footprint, according to the company.

Availability: September 2012 onwards.

Vesuvius



Vesuvius' SOLAR Crucible MLC offers higher yield mono-like silicon ingots

Product Outline: Vesuvius, which provides an extended range of refractory products used in the manufacturing of thin-film and polycrystalline solar panels, has introduced the SOLAR Crucible MLC, a crucible used for the fusion and crystallization of polysilicon in the manufacturing of mono-like silicon ingots. The system has been specially engineered to match mono-like special requirements.

Problem: Improving both the high-purity and yield of quasi-mono ingots is key to reducing costs and enabling the wider adoption of the technology.

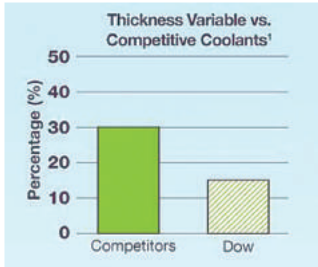
Solution: SOLAR Crucible MLC is a coated 'mono-like' crucible designed to optimize mono-crystal growth in multicrystalline ingot growth furnaces, leading to higher yields of mono-like wafers per ingot. The crucible combines unique and proprietary composition, geometrical parameters and manufacturing processes, enabling an increased yield of mono-crystal wafers per ingot. In particular, the crucible presents extremely high internal bottom flatness that ensures a perfect seed alignment. Such alignment is critical to preventing undesired multicrystallization at the vertical of seed interfaces and to disrupting the targeted mono-crystal growth. Thermal gradients within the silicon melt are another source of undesired multicrystallization phenomena. To prevent such thermal gradients, SOLAR Crucible MLC enables high and homogeneous heat convection along the entire bottom surface of the crucible.

Applications: Silicon ingot casting in multi-crystallization furnaces using mono-cast technology.

Platform: Each SOLAR Crucible MLC is designed to ensure safety in operation and to prevent any leakage. Packaging is available in both industrial and laboratory sizes depending on customers' needs.

Availability: September 2012 onwards.

Dow Chemical



Dow Chemical develops special coolant for improved diamond wire ingot squaring

Product Outline: The Dow Chemical Company has developed a diamond wire ingot squaring coolant that improves PV wafer manufacturing efficiency while also improving the sustainability of the production process. ENLIGHT DC-8300 Coolant is water-based and provides better cutting precision and efficiency.

Problem: Next-generation diamond wire saws are designed to reduce overall PV manufacturing costs by using a higher cut speed and fixed abrasive technology instead of loose abrasive slurry for cutting. Improving the cutting precision and efficiency via new coolants could help accelerate the adoption of diamond wire cutting, helping the industry progress in its goal to reduce cost per watt.

Solution: Because of its suspension and dispersion capabilities, ENLIGHT DC-8300 Coolant is claimed to reduce the percentage of bricks with high thickness variables. The coolant was said to have demonstrated during customer trials that it could significantly reduce ingot defects and was easy to handle, offering a clean ingot-cutting process, as it reduced stickiness issues on the guide roller and on the machine interior parts. The coolant could also sustain multiple rounds of cutting, thus helping to improve customers' production efficiency.

Applications: Diamond wire ingot squaring.

Platform: Water-based ENLIGHT DC-8300 Coolant offers a better environmental profile than glycol-based coolants in the marketplace. In addition, it enables easier silicon powder separation, thus offering higher potential for waste silicon recycling.

Availability: September 2012 onwards.

Challenges for the PV materials supply chain

Mark Thirsk, Linx Consulting LLC, Mendon, Massachusetts, USA

ABSTRACT
The cost of PV modules manufactured and sold in 2012 is highly reliant on the materials used in the construction. A significant part of the market price is driven by the bill of materials, while other direct costs and depreciation form a small proportion of the total cost. Changes within the supply chain, and in the cost of the materials needed and used, are extremely important influences on the module cost and the end market price. In 2012 we have seen a slowdown in growth in the installation of both commercial and residential PV, despite dramatic falls in module costs. Some of the trends and effects of these changes on the materials supply chain for PV modules will be examined in this paper.

Introduction

Economy
As is painfully documented each day in the financial press, the world economy is in a poor shape. GDP growth in all the major markets for PV is weak, with the USA and Japan achieving only 2.1% each, the euro area shrinking by half a per cent, and even China growing at a relatively meagre 7.8% in 2012. Driven in part by these low growth rates, long-term government bond rates have dropped to near-historic lows. With internal rates of return higher than the long-term bond rates, this makes borrowing cheaper and increases the attractiveness of solar installations. In the USA and Europe 10-year bond rates are currently at 1.6 and 1.4%, respectively: a low investment return bar to overcome.

An obvious obstacle to the growth of the PV industry is the relative scarcity of investment capital; nevertheless, attractive projects are finding funding, and installations are proceeding.

“An obvious obstacle to the growth of the PV industry is the relative scarcity of investment capital.”

Cleantech
The entire cleantech industry remains at the mercy of the political process in each region and country. Changes in government in the USA and China have generated uncertainty as to the willingness of the new administrations to continue earlier policies. In the USA there is new optimism that there will be ongoing support for the cleantech industry, but in China the new leadership has yet to indicate its intended direction. In Europe the continued adoption of severe austerity measures plays against the momentum of the cleantech industry for continued adoption of PV if funding is available.

An interesting twist to the situation in the USA is the recent report from the International Energy Agency (IEA) [1] that predicts the USA could become the largest producer of energy in the world and produce 90% of its own energy requirements through the adoption of new extraction technologies. This has been the stated goal of Congress for several years now, and efforts to implement such energy independence may be at the cost of renewable sources.

These unknowns continue to generate uncertainty in the future trajectory of solar PV, which in turn discourages strong investment from value chain participants, local administrations and national governments. While consistent, long-term strategies will help to reduce this uncertainty, economic conditions are unlikely to improve enough to allow the luxury of such strategies in the medium term.

The bill of materials
Clearly, solar module manufacturers have exercised parallel strategies to maintain competitiveness in the market through 2012. On the one hand, rapid adoption of new technologies – such as the formation of selective emitters, reduced silver pastes and narrow contact grids and busbars to increase cell efficiency – have improved the output of each module sold. On the other hand, relentless pressure has been exerted on the supply chain to reduce costs, while maintaining material properties and quality. At all levels of the supply chain, aggressive cost-cutting and efficiency improvements have been implemented in an attempt to meet customer expectations; this has not, however, prevented significant reductions in profit margins at all levels of the chain. At a time when major suppliers have had to commit to significant capacity increases to meet the rapid demand in growth, reducing margins and cutting costs have challenged the business model assumptions of the suppliers.

	Cost ($/Wp)
Silicon	0.0841
Gases	0.0043
Wet chemicals	0.0150
Dopants	0.0296
Pastes and inks	0.0992
c-Si EVA	0.0236
c-Si backsheet	0.0477
c-Si glass	0.0488
Stringers	0.0202
Framing	0.0578
Total	0.4303

Table 1. Material costs for c-Si modules (2012).

“There has been a steady reduction in commitment to the PV industry from larger companies.”

	Cost ($/Wp)
Mo	0.0009
Cu	0.0002
In	0.0099
Ga	0.0181
Se	0.0012
H_2Se	0.0066
CdS	0.0006
DEZ	0.0002
EVA	0.0222
PVB	0.0001
Edge seal	0.0008
Glass	0.2084
Total	0.2692

Table 2. Material costs for CIGS modules (2012).

Materials

Supply chain trends

To those visiting PV exhibitions and conferences in the last 12 to 18 months, the trends within the supply chain have perhaps been very obvious. There has been a steady reduction in commitment to the PV industry from larger companies, coupled with high-profile bankruptcies of suppliers and module manufacturers alike, evidenced by the declining number of exhibitors. These problems are also evident in the financial statements of players at all levels of the value chain, and financially weaker players continue to experience poor performance in this market. While the diversified suppliers can offset PV segment performance with other segment results, pure-play PV suppliers have significant ongoing challenges.

Against the background of continuously reducing the price per watt of finished PV modules, the downward cost pressure is unlikely to relent, and any expectations of some recovery in module pricing will only be met by howls of protest from installers looking for cheaper modules.

Crystalline silicon

Crystalline silicon (c-Si) cells and modules still comprise more than 80% of module sales and have been the focus of most technology improvements and cost-cutting efforts. A significant proportion of module price cuts have been achieved on the back of reducing polysilicon costs and increasing the efficiency of material use. A cost of silicon between the mid-20s and high teens is currently reported. Prices in this range still afford a narrow profit margin for the most efficient suppliers, but will probably not be sufficient for reinvestment in the long term; many smaller suppliers, however, have mothballed production, being unable to compete at this price level.

The adoption of new technology in leading-edge modules has been accelerated in 2012 by the use of novel materials such as nanocrystalline inks, dopant pastes, printable etchants, pastes with reduced silver content, and enhanced adhesives and backsheets. Most leading manufacturers have developed high-efficiency modules with monocrystalline silicon, reaching conversions of 19 to 20%, while improvements in processes, materials factory automation and process control have helped push up median cell efficiency numbers for all cell types. Material suppliers have helped implement many of the technologies that have led to these efficiency improvements while also aggressively reducing their selling prices through cost-cutting, operational efficiency improvements and margin reductions. Following a significant period of market growth and capacity addition, many suppliers have reported financial losses in 2012 at the same time as having to digest increased depreciation due to plant additions for capacity increases. Many companies have publicly stated that they are reviewing the strategic options for divisions serving the PV industry, and a consolidation of the supply base is expected over the next 12 months.

The rapid expansion of demand for many materials has been addressed by larger manufacturers through strategies of scale. To serve Tier 1 and Tier 2 cell and module makers, suppliers have had to develop robust large-scale manufacturing operations, often at multiple locations. In the case of many materials – for example polysilicon and backsheet polymers – investment in new manufacturing capacity is hugely expensive and has to be done on a large scale to remain economic. The wisdom of capacity addition in such large blocks is currently open to question, since the growth in material demand has declined in many segments, making it difficult for these investments to meet their planned returns.

The most common polymers used in module manufacture are almost all oil derivatives. Although the majority of these polymers have been manufactured in the USA, the increasing availability of cheap shale gas in North America is shifting the chemical industry away from oil as a raw material. In the medium to long term this will probably favour North American chemical manufacturers as suppliers of encapsulation polymers and backsheets, as long as conversion capacity to gas feedstock is developed.

The main exceptions to this are fluorinated materials, which continue to be supplied predominantly by the USA and Japan. The driver for fluorinated polymers is the increased lifetime available with these UV-resistant materials. The price premium for such improved performance is, however, becoming less and less popular, and module makers are evaluating alternative materials for backsheet cladding. Anecdotal evidence exists which indicates that some of these lower-cost backsheets may be resulting in early returns of installed modules, although this has not been widely confirmed.

"The promise of thin-film modules to deliver very low-cost modules has not been universally kept by the competing manufacturing technologies employed."

Thin film

The promise of thin-film modules to deliver very low-cost modules has not been universally kept by the competing manufacturing technologies employed. With the exception of First Solar and their CdTe absorber technology, other thin-film technologies have struggled to develop reliable manufacturing methods and large-scale production capacity. Many of the thin-film deposition precursors are gaseous and supplied through the major gas suppliers. Since 2008 the high price of polysilicon, and the promised low cost of thin-film technologies, have persuaded gas suppliers to invest in large-volume supply capability for materials such as silane, germane, cadmium selenide and other bulk gases. Similarly, manufacturers of sputter targets have committed resources for developing copper-alloy targets and supply chains for the rare metals used in CIGS absorbers. All of these suppliers have been frustrated by the lack of growth in these markets, and to a great extent have disassembled, at considerable cost, the business units designed to supply the demand.

The supply chain environment

As discussed, practically all of the material supply chain has experienced a range of financial challenges in 2012. These challenges include profit margin collapse, combined with slowing demand, and the continued concentration of manufacturing in China, Taiwan and Korea. Most suppliers are hardly profitable or losing money in supplying to the PV industry. Many of them entered this segment from other electronics industries or other specialty markets, and, although familiar with demand volatility, are not meeting their financial expectations. This has led to a change of strategy in addressing opportunities in the PV market: the reaction has been an almost across-the-board reduction in resource allocation to this market. This includes moving managers and other personnel to other business units and reducing sales and marketing efforts for PV products, while R&D focus has shifted to segments with higher perceived returns. These changes will result in reduced focus by many of these companies on the market, and slowing of the pace of innovation for the PV market.

In China there has been an increase in the number of companies offering materials for module construction, but the learning curve is steep and new entrants have a lot to learn before offering world-class products. Domestic Chinese suppliers who spotted an opportunity in the PV market five to ten years ago have certainly been able to improve their product offering to world-class standards, but these companies are now experiencing the same difficult financial conditions and will struggle to invest at the rate required to continue innovation.

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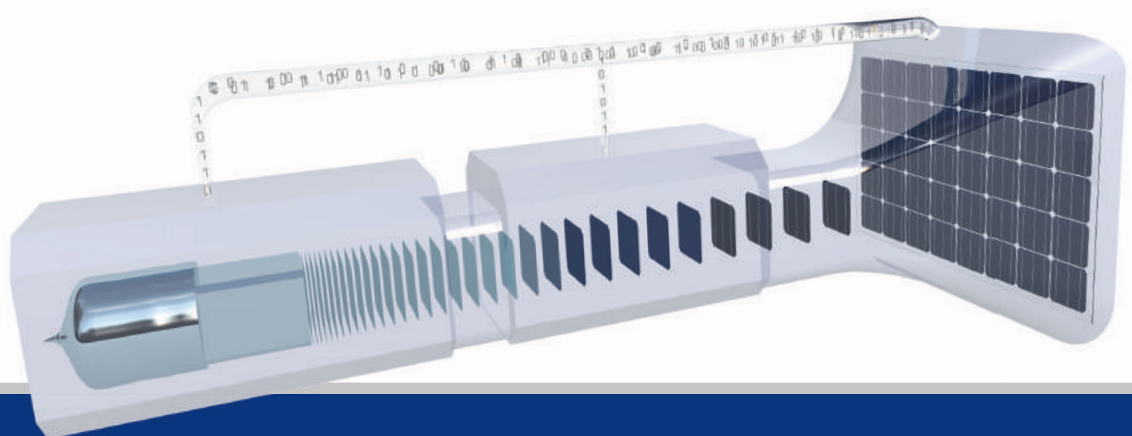

The turmoil in the PV industry over the last 18 months has taken place at a time when raw material prices have been relatively stable. Price fluctuations in oil and precious metals, such as silver, have meant that, while these raw materials have a significant impact on overall cost, no price spikes have been passed on to the end customers. However, history tells us that this will change, and, with narrow margins, suppliers will struggle to maintain end-market prices if raw material prices spike in the global commodity markets. Price increases in cell- and module-making materials will also lead to price increases of the finished modules, upsetting the perception of monotonic reductions of cost per watt for modules.

"As margins decrease, barriers to adopting innovation will increase and budgets for the development of novel materials will decline."

The bottom line

What, then, is the conclusion for watchers of the PV industry? We are seeing continued rapid change in the PV industry. The steep module price declines of the last 12 to 24 months have resulted in more-competitive PV installations that are approaching economic competitiveness with other forms of centralized generation, but probably still have some way to go. Assuming that sufficient governmental and popular support for PV continues, the industry will continue to develop.

Supply chain participants will make strategic and tactical decisions on the basis of current and past situations. The migration of the materials supply segment from a high-margin, specialty industry to a large-volume, low-margin segment will change the character of this market. We would expect three major effects from this migration:

1. In the medium to long term it is likely that there will be a decline in pure-play material suppliers. We would expect these suppliers to be acquired by others (or merge their operations with them) to develop larger businesses more adapted to conditions in the PV industry.

2. The industry will move to more closely resemble a global commodity-supply chain, with material sourcing and production located for maximum efficiency, and scaled to meet the expectations of the customer base. There will be a reduction in the number of specialty players in the supply chain, and many of those companies that may have brought innovative technology will exit if their margin expectations are not met.

3. As margins decrease, barriers to adopting innovation will increase and budgets for the development of novel materials will decline. It will become increasingly difficult for new solutions to gain traction and scale quickly enough for large-volume adoption, unless those innovations are supported by large companies.

In making these predictions it is assumed that crystalline silicon will continue to be the product of choice for large-scale PV installations. In the short term this will very likely be the case. However, the material efficiency and the manufacturing benefits of thin-film technologies should not be neglected – these may still offer significant opportunities for material and process innovation and business growth.

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About the Author

Mark Thirsk is a managing partner and co-founder of Linx Consulting, which provides market-defining analysis and strategic insights across major markets in electronic materials. He has over 25 years' experience in economic and business forecasting, strategic planning, technical marketing, product management and M&A, spanning many segments and processes in electronic materials. Mark has served on the SEMI Chemicals and Gases Manufacturers Group (CGMG) since 1999, acting as chairman between 2001 and 2003. He holds a B.Sc. (Hons.) in metallurgy and materials science from Birmingham University and an MBA from The Open Business School, and has authored multiple publications in both academic and trade publications, as well as contributing to several patents.

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Polysilicon production technologies in a volatile market

Johannes Bernreuter, Bernreuter Research, Würzburg, Germany

ABSTRACT

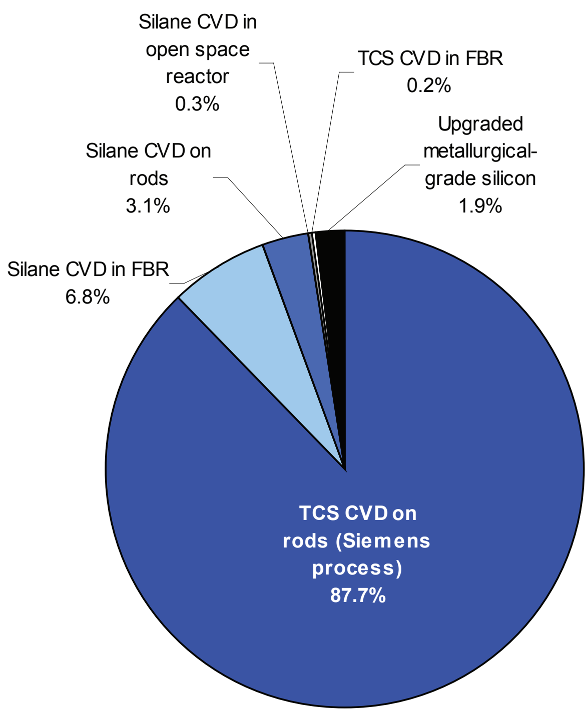
A record-low spot price in the wake of oversupply and the aggressive cost-reduction roadmap of the PV industry are putting polysilicon producers under pressure to bring down their manufacturing costs. With the dominant Siemens process approaching a limit for further cost cuts, technologies based on the deposition from monosilane (SiH_4) have now become the focus of attention.

Challenge of a cyclical business

After the polysilicon spot price began its five-year-long rally from a low of US$24/kg in 2003, the reaction took a while; but then, new production facilities were springing up like mushrooms in China. A lot of them were small 'chanterelles': 19 of the 43 Chinese polysilicon manufacturers in 2011 had an annual production capacity not larger than 1500 metric tons (MT), and eight of these were even 500MT or under. Such mini plants did not use a closed loop for recycling the vent gas silicon tetrachloride and consumed more than 300kWh of energy for 1kg of polysilicon, resulting in manufacturing costs of up to $70/kg.

This was a business model built on a perpetual high spot price, not on reality. Clearly, those small entrepreneurs were unaware of one fundamental characteristic of the polysilicon business: its cyclic nature. Since the engineering, construction and ramping-up of a new polysilicon plant can easily take three years, supply will always lag behind demand, leading to a regular cycle of oversupply and shortage phases with strong price fluctuations.

Now that the spot price has crashed from its high of $500/kg in 2008 to a record low of $15/kg, even the largest Chinese polysilicon manufacturers feel the brutal pressure of oversupply. They have successfully applied to the Chinese Ministry of Commerce for an anti-dumping and countervailing-duty investigation of polysilicon imports from the USA, South Korea and Europe – an obvious reaction to similar investigations in the USA and the European Union on China-made wafers and solar cells. Such tit for tat, however, does not solve the real problem. The polysilicon industry in China needs to work on reducing manufacturing costs and improving the product quality.



Source: Bernreuter Research

Figure 1. Market shares of technologies in the polysilicon production volume of 2011.

"A widely accepted, yet aggressive, target for the manufacturing costs of crystalline silicon solar modules is approximately 0.5US$/W by 2016."

Pressure from the PV industry

Although prices will recover on their way to the next shortage, which Bernreuter Research expects to happen in 2016, manufacturers cannot rest on this perspective. Since 1998 the share of the PV industry in polysilicon demand has risen from practically zero to almost 90%. Thus, the radical cost-reduction roadmap of its most important customer will have far-reaching implications for the polysilicon industry.

A widely accepted, yet aggressive, target for the manufacturing costs of crystalline silicon solar modules is approximately 0.5US$/W by 2016. Based on long-term contract prices, the share of the polysilicon feedstock in total module manufacturing costs has been varying in a relatively narrow band of 15 to 20% over the last few years. If this share is not to exceed 20%, and the average specific silicon consumption decreases to 5g/W by 2016, a polysilicon price of $20/kg will be required. Obviously, this is not a sustainable level for manufacturers. Their customers will be forced to further reduce the specific silicon consumption and to accept that polysilicon will take a higher share in the module cost structure. With 4.5g/W and a share of 25%, a price of nearly $28/kg would still be tolerable.

The high cost pressure, however, could promote a new trend in the PV industry towards fully integrated production from polysilicon to module in order to shave the profit margin of another step in the value chain – in particular when a new shortage drives up the polysilicon price considerably. The pressure is high because module manufacturers will hardly be able to fully pass on such a price increase to the end customer: there will be no generous solar incentives available that could cushion a module price hike of 30% as there were during the bottleneck between 2004 and 2008.

Cost limit for the Siemens process

For the reasons mentioned above, it is therefore in the polysilicon producers' interest to bring down their manufacturing costs as well. The dominating technology – the Siemens process – has been very successful in achieving a significant reduction of costs over the last decade, resulting in a market share of 88% in 2011 (Fig. 1). This development has mainly been driven by an enormous increase in the productivity of reactors for the chemical vapour deposition (CVD) of silicon from trichlorosilane (TCS) and by hydrochlorination as a more efficient technology to recycle silicon tetrachloride back to TCS. In October the equipment supplier GT Advanced Technologies, Inc. (GTAT) announced a new hydrochlorination fluidized bed reactor (FBR) for plants with an annual polysilicon production capacity of more than 10,000MT; according to GTAT, it allows cash costs to be reduced to less than \$14/kg. Assuming a depreciation rate of \$6/kg to \$8/kg, this would result in manufacturing costs of \$20/kg to \$22/kg.

Most experts, however, agree that the air is getting thin for the Siemens process to improve on \$20/kg. One should not let oneself be blinded by the figure of \$18/kg that GCL-Poly Energy Holdings Ltd. claims for its subsidiary Jiangsu Zhongneng Polysilicon Technology Development Co., Ltd., China's largest polysilicon producer. Its actual manufacturing costs are substantially higher.

> "Bernreuter Research has identified technologies based on the CVD from monosilane as a viable alternative to the Siemens process."

In the current polysilicon market report "The 2012 who's who of solar silicon production" [1], Bernreuter Research has identified technologies based on the CVD from monosilane (SiH_4, also referred to in short as silane) as a viable alternative to the Siemens process. Just one week after this result was presented during the 27th European Photovoltaic Solar Energy Conference (EU PVSEC) in late September 2012 [2], GCL-Poly announced it had accomplished the trial run of its first-phase monosilane production system and was working on FBR technology to manufacture polysilicon from monosilane.

Deposition from silane on rods

CVD from monosilane is anything but a new technology in the polysilicon industry. In the second half of the 1970s, Union Carbide Corp. (UCC) developed a catalytic disproportionation process that converts TCS via dichlorosilane and monochlorosilane into monosilane; in 1984 the company opened a polysilicon plant in Moses Lake, Washington, USA, which was later run by Advanced Silicon Materials Inc. (ASiMI) and is today owned by REC Silicon Inc. The design of the CVD reactors was developed by Komatsu Electronic Metals Co., Ltd.; it is optimized to achieve extremely smooth and uniform polysilicon rods that can be converted into monocrystalline ingots for the semiconductor industry through the float-zone method.

Because of this optimization process, the deposition rate in the Komatsu reactor is very low, with a rod diameter growth of only 0.5mm/hour, compared to a rate of 1–2mm/hour in a TCS-fed Siemens reactor. Moreover, the Komatsu reactor cools each single silicon rod individually in a separate chamber, which consumes a lot of energy. This design has to do with a specific property of SiH_4: at temperatures above 500°C, it readily decomposes into silicon dust and H_2 instead of depositing silicon on the filaments.

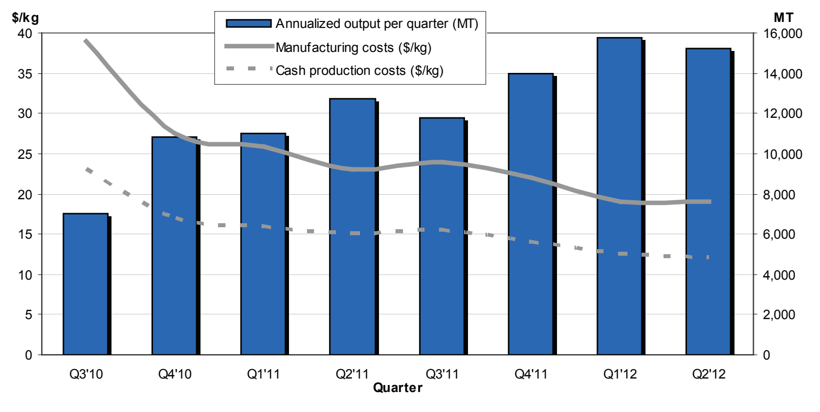
Schmid Silicon Technology GmbH (SST) has developed a way of reducing the rate of silicon dust formation below 2% and increasing the silicon deposition rate to 1 mm/h: details are discussed in Bernreuter [1]. SST's affiliate Schmid Polysilicon Production GmbH is running a semi-commercial plant in eastern Germany with an annual silane capacity of 540MT and a 180MT CVD reactor for test campaigns. For a 6000MT plant with an electricity rate of 0.08US\$/kWh, SST projects manufacturing costs of \$21/kg and cash costs of \$13/kg.

At best, this would give the approach a slim cost edge over the Siemens process. Advantages are the high polysilicon purity of up to 11N and the marketable co-product silane. Lyle C. Winterton, an international silane expert who worked at UCC/ASiMI/REC for 25 years, regards Schmid's technology as the "best option in today's market", but he relativizes: "Monosilane CVD and TCS CVD have essentially the same cost." While silane avoids the complex vent-gas recovery of the Siemens process, its CVD is "much more difficult to run", says Winterton.

Silane in a fluidized bed reactor

As the announcement of GCL-Poly shows, the trend is towards CVD from silane in an FBR, in which tiny seed particles grow to polysilicon granules. Industry insiders say that a couple of other companies are working on silane-based FBR technology as well as GCL-Poly. Even Dow Corning Corp., which opened a 4000MT silane plant adjacent to the Michigan site of its polysilicon subsidiary Hemlock Semiconductor in August 2011, is reportedly considering bolstering its FBR research division.

The technology itself is not novel either. In 1987 Ethyl Corp. started up a silane-based FBR polysilicon plant in Pasadena, Texas, USA, which has been run by MEMC Electronic Materials, Inc. since 1995. Although FBR technology provides the advantage of very low energy consumption, the Pasadena plant cancels this out by Ethyl's expensive silane route, which applies the reduction of silicon tetrafluoride (SiF_4) with sodium aluminium hydride ($NaAlH_4$). The new 10,000MT FBR plant that MEMC is currently building in a joint venture



Sources: REC, Bernreuter Research estimates

Figure 2. Annualized output and manufacturing costs of REC Silicon's FBR plant in Moses Lake.

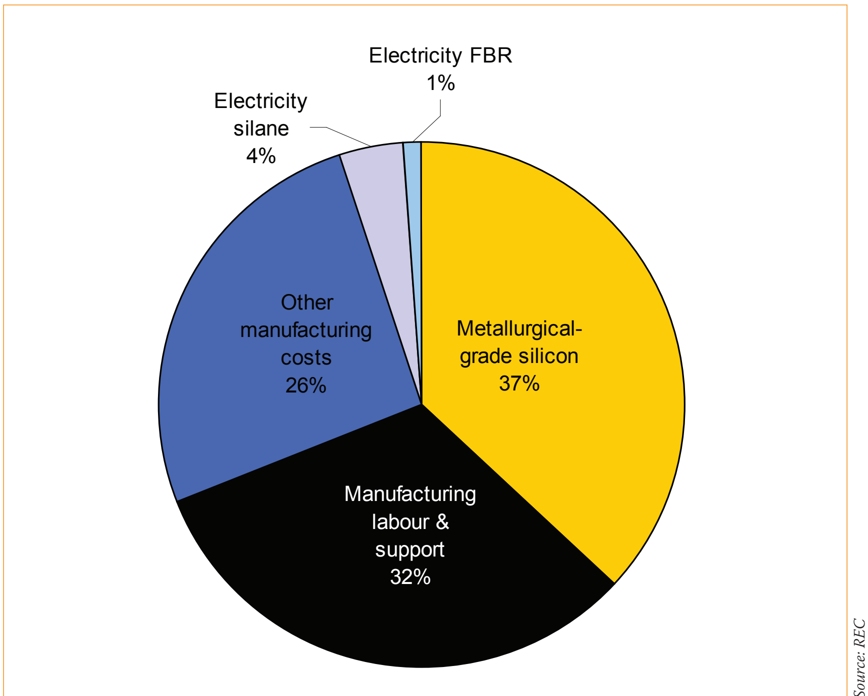


Figure 3. Breakdown of REC Silicon's FBR manufacturing costs.

with Samsung Fine Chemicals Co., Ltd. in South Korea will therefore use the disproportionation of TCS.

What has raised awareness of silane-based FBR technology is the progress that REC Silicon has made with its FBR plant in Moses Lake over the last two years. After start-up problems in 2009, the run rate has, remarkably, increased from the initial design capacity of 10,500MT to over 15,000MT in the first half of 2012. As a result, the manufacturing costs have dropped to $19/kg and the cash costs to $12/kg (Fig. 2).

> "REC presented a preliminary cost projection for an FBR plant in China with manufacturing costs of $11.3/kg and cash costs of $7.9/kg."

At the 6th SNEC PV Power Generation Conference in 2012, REC presented a preliminary cost projection for an FBR plant in China with very aggressive figures: manufacturing costs of $11.3/kg and cash costs of $7.9/kg [3]. Compared to REC's plant in Moses Lake, the capital expenditure is reduced by more than 50%, owing to both an optimized plant design and a local savings in China. Since electricity consumption cost only makes up 5% of the total manufacturing costs (Fig. 3), other savings mainly come from lower Chinese prices for labour and for the raw material metallurgical-grade silicon.

Looking towards the future: the push for high-efficiency cells

So far, one drawback to REC's polysilicon granules has been their high metal content, originating from the reactor wall. However, this contamination can be prevented by a removable liner. It requires a very sophisticated design such as that developed by MEMC. Indeed, in October, REC announced it is planning to introduce electronic-grade granules in 2013.

While a fifty–fifty mixture of granules and conventional chunks from polysilicon rods can shorten the time to fill a crucible by 40% and increase the charge weight by 30%, the particular value of granules lies in their being well suited to the continuous recharge of single crystal pullers working with the Czochralski (Cz) process. Continuous Cz technology promises both a better quality of crystal and a substantial cost reduction over the expensive batch Cz process. GTAT is aiming to introduce a continuous Cz system in 2013. This innovation has the potential to decisively promote monocrystalline high-efficiency cells, which have dominated the crystalline silicon section of EU PVSEC since 2011. The synergy between granular polysilicon and continuous Cz technologies could thus shape a powerful trend: perhaps in 2016, monocrystalline high-performance cells with efficiencies exceeding 22% will be more prevalent than many dare to imagine today.

> "Continuous Cz technology promises both a better quality of crystal and a substantial cost reduction over the expensive batch Cz process."

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About the Author

Johannes Bernreuter is head of the polysilicon market research firm Bernreuter Research, which he founded in 2008. Originally an associate editor for the PV magazine *Photon*, Johannes authored his first analysis of an upcoming polysilicon bottleneck and alternative production processes as early as 2001. He was awarded the prestigious RWTH Prize for Scientific Journalism by RWTH Aachen University.

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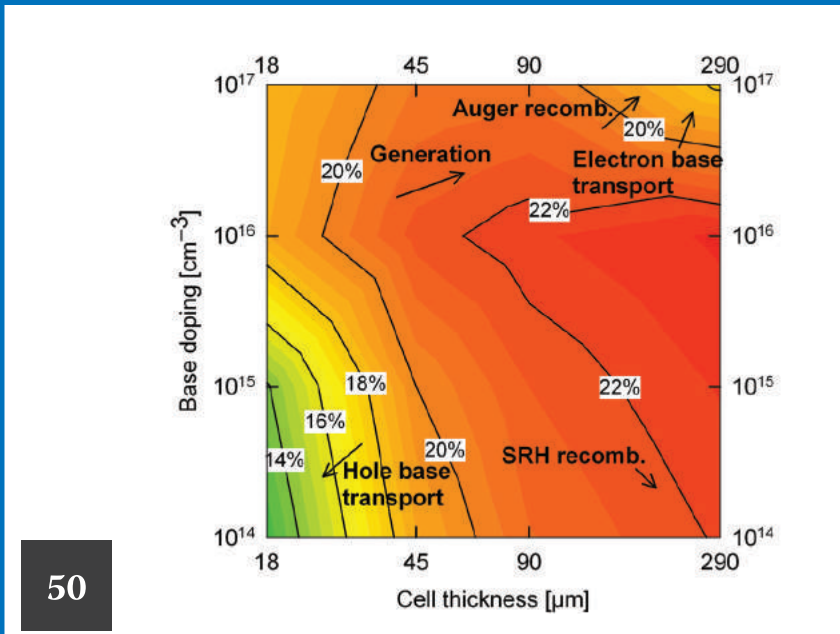
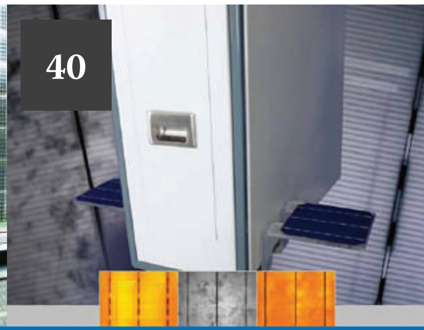
Cell Processing





News

Sunways achieves higher peak performance in PV cells

German PV manufacturer Sunways has increased the peak efficiency of its solar cells to almost 20%, the company has announced.

Using new manufacturing techniques, Sunways claims its series-produced PV cells have achieved peak efficiency values of 19.4%. Efficiency describes the percentage of radiant energy converted into electrical energy.

Sunways said this performance had been achieved by optimising various features of the cells, such as front metallization and surface structure, and resulting in increased light yields through minimisation of shading and reflection losses.

The measurement had been confirmed by the PV calibration laboratory of the Fruanhofer Institute for Solar Energy Systems in Freiburg, the company added.

A solar module comprising 60 solar cells with an efficiency of 19.4% generates an output of around 270 watts.

Source: Sunways

Sunways cells are now more efficient.

Natcore scientists develop "blackest" silicon solar cell surface

From the heart of its R&D centre in Rochester, New York, Natcore Technology scientists have developed what they call the "first black silicon solar cell".

Using scalable liquid phase deposition (LPD), scientists developed the technology from wafer to cell. The silicon wafer is said to have a near-zero reflectivity; however, Natcore stresses that the wafers are only components of a solar cell and are not able to produce electricity until formed into solar cells.

The company noted that prior to its US$2.5 million financing, which was completed in July, it would have normally outsourced the production steps and tests for its latest technology to other labs. However, portions of its proceeds from this summer led to it using its in-house technology in order to develop what it marks as the "blackest" silicon solar cell surface to date.

The company plans to partner with the National Renewable Energy Lab (NREL) under a cooperative research and development agreement. The NREL and Natcore will work on using Natcore's LPD technology and the NREL's technologies in order to reach, or exceed, record efficiency with the black silicon solar cells.

Hao-Chih Yuan, NREL research scientist, noted: "We have a good synergy with Natcore on black silicon technology. A silicon surface, without proper coating, is detrimental to the energy conversion efficiency of the solar cell. It is not unusual to grow silicon dioxide coatings on black silicon surfaces for this purpose, but the growth is typically at very high temperatures. Natcore's coating uses chemistry. They are the ones who can passivate a black silicon surface cheaply."

Solar cell makers still waiting to see impact from Kyocera's 3-busbar patent

A report from the DigiTimes has revealed that solar cell makers are still waiting to see what impact, if any, Kyocera's patent for its 3-busbar solar cell structure will have on their businesses. Issued in Japan on September 4, different media outlets speculated that Kyocera may use the patent to stop other solar cell makers from manufacturing 3-busbar products.

If Kyocera does decide to put restrictions on other solar cell makers, manufacturers may have to contend with the possibility that 3-busbar solar cells will not be exported to Japan or, conversely, that they will need to pay Kyocera patent fees.

Kyocera's 3-busbar solar cell sports a width of 0.5-2mm between busbars, a finger electrode width of 0.05-0.1mm and one busbar placed in the middle of the cell. Other cell makers have advised that almost all firms manufacture 3-busbar solar cells in this manner and fear that if Kyocera uses the patent to limit other firms, most 3-busbar manufacturers will be affected.

DigiTimes noted that Wen-Whe Pan, president and COO of solar cell company Gintech, felt that it would come down to a customer's preference of using 2- or3-busbar solar cells. Sam Hong, president of Neo Solar Power, further noted that if the patent is used by Kyocera to limit other companies like his own, NSP may switch capacity to 2- or 4-busbar.

SunPower at loss over Europe: Ramping 'Gen 3' cell technology

Having already pre-announced its latest manufacturing restructuring plans, SunPower's management reiterated the unspecified temporary idling of 6 of 12 production lines at Fab 2 and a reduction in its overall capacity utilization rate to around 60% in Q4 2012.

The company is meeting PV project module delivery schedules via support from its high inventory levels, which are also helping to support a 10% inventory reduction in Q3.

SunPower reported cell production of 227MW, down around 10% from the prior quarter.

Management said that it remained on target to have achieved a 25% reduction in its blended cost per watt at year-end. The company said this would be achieved by a combination of 'higher yields, improved overall equipment effectiveness and lower raw material cost.'

Management highlighted that its silicon utilisation in Q3 2012 reached 4.8 grams per watt, the first time the figure had gone below 5 grams per watt.

With respect to its continuing step reduction program, SunPower noted that production lines at Fab 2 had been retrofitted to run the new process, which claims to reduce line process steps by 15%. The program was said to be a full quarter ahead of schedule. Conversion of Fab 3 to the process reduction plan would be undertaken in 2013.

The company also noted in the conference call that it was ramping production of its next-generation 'Gen 3' technology, which has a cell efficiency of up to 24%. Installation of new equipment was ongoing, having started in Q3.

As a direct result, capital expenditure for the full-year has remained relatively unchanged at between US$115 million and US$125 million. Capital expenditures in the fourth quarter is expected to be in the range of US$30 million - US$40 million.

SunPower said that production of Gen 3 technology would reach near to 100MW by the end of 2013.

Leading PV manufacturer undertaking tool evaluations with start-up

According to Aurora Control Technologies (ACT), one of the top 10 PV manufacturers in 2011 will soon be making a full tool evaluation of its Decima CD measurement instrument. The agreement was signed at the EU PVSEC event, held in Frankfurt, Germany.

The Decima CD is an inline, non-contact emitter dopant (sheet resistance) measurement system featuring whole-wafer mapping at full production throughput, for 100% profiling of processed

Source: Aurora Control Technologies

The Decima CD is an inline, non-contact emitter dopant measurement system.

solar cells. According to the company the system enables up to 100 measurement points per wafer in real time, for both batch and inline diffusion production lines.

The company said that the tool evaluation will consist of three phases that include both laboratory and live production-line testing as well as the possibility of a commercial production line rollout upon completion of testing, subject to the evaluation process. ACT noted that should that occur it would become a top-tier manufacturing line reference installation, for the start-up.

Solar Junction's solar cells reach new record for energy efficiency

Solar Junction has announced that its multi-junction solar energy cells have set a new world record for energy efficiency of a commercial-ready production solar cell. The company advised that the National Renewable Energy Laboratory (NREL) verified that the power conversion efficiency of its cells measured 44% at 947 suns, beating its own previous 43.5% at 418 suns record.

"Breaking our own world record cements Solar Junction as an innovator and leader in the multi-junction cell space," said Vijit Sabnis, VP Technology at Solar Junction. "We continue to push technological boundaries to further drive CPV costs down."

Business News Focus

Manz cites evaporating solar bookings as sales decline 23.1%

A significant fall in orders and bookings within Manz's solar division were partially offset by increased business within its display division, the specialist equipment supplier has reported.

The company said that revenue for the first nine months of 2012 reached €147.7 million, compared with €192 million in the previous-year period, a 23.1% decline. The company reported negative earnings before interest and tax (EBIT) of €3.5 million, compared to €3.8 million last year.

The solar division reported revenue of only €14.9 million, down significantly from €57.9 million in the same period a year ago. Manz noted that solar segment sales had made up 30.2% of total sales in the same period last year, while only reaching 10.7% in 2012.

The company noted in its nine month financial statement that solar segment sales had declined four quarters in a row, despite the majority of its R&D spending having been focused on the solar segment. Manz noted that R&D spending reached 9.3% of total sales in the period covered.

Dieter Manz, CEO of Manz AG, said: "Over the last few years, we have successfully further developed our company from an automation specialist into a supplier of integrated production solutions. We have successfully diversified our business model with our strategic business units, display and battery. The positive order situation in both segments has allowed us to partly compensate the revenues and earnings declines in the solar segment. With an approximately 21% year-on-year revenue increase the display segment has developed very positively."

Major management reshuffle at centrotherm photovoltaics with Dr. Peter Fath out as CTO

Continuing to restructure the company in hope of surviving the solar shakeout, major PV equipment specialist centrotherm photovoltaics has made sweeping changes to its senior management with the notable fall of its enigmatic CTO, Dr. Peter Fath. Current CEO, Robert M. Hartung will also step down from his position, while Peter Augustin will become responsible for core solar cell and module business, amongst other management changes.

Although Dr. Fath has lost his CTO role and stepped down from the management board, centrotherm said that he would "remain connected with the company", including "continuing to support and drive further ahead with activities in the MENA region, particularly in Algeria".

Hartung, former CEO, will also step down from the management board and join the supervisory board succeeding his father, company founder Rolf Hartung, as a supervisory board member as part of succession arrangements.

Jan von Schuckmann, previously chief restructuring officer, is to have been appointed CEO. Tobias Hoefer is to remain the management board member responsible for the company's self-administration and for the implementation of the restructuring program.

Peter Augustin, most recently CEO of centrotherm thermal solutions and centrotherm cell and module department, would be in charge of the company's core solar cell and module business, as well as responsible for the diversification within the semiconductor and microelectronics sectors.

Hans Autenrieth, a co-founder but involved in only consultancy roles is also expected to rejoin the company and become a management board member and reassume responsibility for sales and marketing.

As part of the restructuring efforts under self-administration, centrotherm said that further management changes would be made.

Singulus Technologies sales reach €83.5 million in Q3

Equipment supplier Singulus Technologies reported Q3 2012 sales of €83.5 million and negative earnings before earnings and tax of -€10.9 million.

The company reported new order intake for the first nine months of the year had reached €110.6 million, down from €137.0

Source: Manz AG

The Solar division reported revenue of only €14.9 million.

million in the same period a year ago. As of September 30 2012 the order backlog stood at €53.9 million, which is slightly above the previous-year level of €50.8 million.

With almost zero debt, Singulus management noted in a statement that it was fully committed to developing its foothold in the solar PV and thin film sectors and had the resources to develop partnerships and projects with potential customers.

However, Singulus said that it was projecting full-year losses of between €54-56 million, with liquid funds amounting €65.4 million as September 30 2012. The company recently announced a major restructuring effort on the back of weak demand, especially from the solar segment.

Little change in NSP's cell demand from China on October

Monthly solar cell sales at Taiwan-based Neo Solar Power Corporation (NSP) increased only 2% q-on-q in October, remaining near record lows as Chinese module manufacturers continue to cut production.

NSP said that sales in October, 2012 reached NT$777 million (US$26.5 million), a 2% increase from sales of NT$764 million in September.

Sales in 2012 peaked in June at NT$1,389 million, significantly below peak sales in August, 2011 when sales reached NT$1,768 million.

Last week, NSP posted Q3 2012 revenue of NT$2,962 million. Gross loss was NT$322 million, with gross margin negative 10.86%.

The solar cell producer said that its financial results had continued to be impacted by overall industry overcapacity within the supply chain as well as being impacted by Chinese producers clearing inventory clearance and resulting fall in average selling prices.

NSP had noted that PV producers continued to scale-down production and reduce workforce levels to better align with overall demand.

Amtech revenue hit by equipment final acceptance delays

PV equipment supplier Amtech Systems has pre-released preliminary full-year results for 2012 on the back of expected heavy losses and equipment final acceptance delays.

Amtech said that it expected to report revenue of US$81.5 million for the full-year, down from record revenue of US$247 million in 2011 financial year.

Revenue in Q4 was said to be US$10.9 million, compared to US$59.9 million reported in the same period a year ago.

Amtech said it expected to report a "significant loss" in its Q4 results, which will be released around November 20, 2012.

Fokko Pentinga, Amtech's Chief Executive, said: "Revenue for the quarter fell short of our guidance due primarily to the timing of final acceptances on several of our solar equipment installations, some of which were subsequently received in October. While the solar equipment industry continues to be affected by over capacity, we work actively with our Tier 1 customers to support their pursuit of lower costs and higher cell efficiencies. We continue to believe in the longer-term solar opportunity and in our high-end diffusion, ion implanter, new-batch PECVD and N-type technologies."

Pentinga also said that further cost reduction plans had been implemented in September, which were above and beyond previous plans already implemented this year, though details would not be disclosed until its fiscal year-end conference call.

PV equipment suppliers are being severely impacted by acute manufacturing overcapacity that has led to a massive reduction in capital expenditures and resulted in an historic negative book-to-bill ratio.

Product Reviews

Despatch Industries

'Safire' dual chamber firing furnace from Despatch tailors thermal profiles around advanced materials and cell architectures

Product Outline: The 'Safire' firing furnace, together with the 'DriTech' dryer, were designed by Despatch Industries to provide PV manufacturers with the ability to properly segment, control and adjust key process parameters. The Safire design features dual, independent chambers with no lane-to-lane influences that are claimed to provide the greatest degree of firing repeatability and capability for cell efficiency optimisation.

Problem: Optimization of process controls, especially for high-performance solar cells, is required to maximise yield and deliver lowest cost per watt. The challenge has been to provide high throughput-volume equipment that provides the required process uniformity to ensure exact profile repeatability.

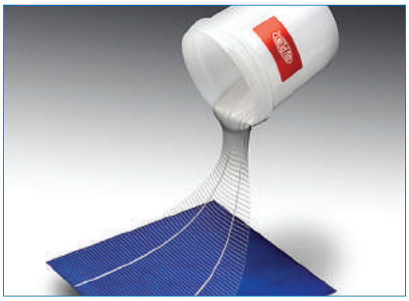
Solution: The Safire is built on the foundation of process separation, stability, high up-time and the ability to tailor thermal profiles around advanced materials and architectures. The new firing furnace has segmented and optimized critical components of the cell process for maximum control and stability. Integrated with the DriTech dryer, the Safire decouples VOC removal from the burn-out process and ensures that VOCs are removed to prevent furnace and facility contamination. Burn-out is separated from firing for proper binder removal, a contamination-free firing zone and a stable, repeatable thermal experience. The Safire's dual independent chamber design eliminates lane-to-lane loading influence.

Applications: Solar cell firing furnace.

Platform: The Safire offers further process optimization through 'Microzone' technology, which provides the ability to precisely tailor the burn-out interval, the time above melting temperature and the peak firing and cooling profiles.

Availability: September 2012 onwards.

DuPont



DuPont offers Solamet PV18A for enhanced LDE cell performance

Product outline: DuPont Microcircuit Materials (MCM) has introduced its next-generation front-side metallisation pastes for crystalline silicon solar cells. DuPont Solamet PV18x series photovoltaic metallisation pastes are claimed to offer improved productivity beyond that provided by the Solamet PV17x series. Solamet PV18A is claimed to be the first metallization paste tailored for optimal performance on monocrystalline wafers with enhanced lightly doped emitters (LDEs).

Problem: Solar cell manufacturers are looking at ways to improve productivity by increasing cell and module efficiencies and lifetimes while keeping their costs in line with rapidly falling module prices.

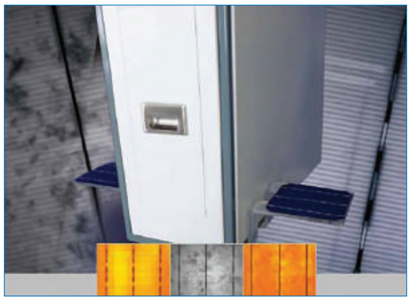
Solution: PV18A is claimed to demonstrate efficiency gains despite significantly less material consumption when compared to Solamet PV17F. MCM is concurrently developing diffusion recipes in-house aimed at boosting solar cell efficiencies beyond the 19.3% level already demonstrated with Solamet PV18A. PV18A is the first version of a new series, and plans are to continue to expand the series to address the specific needs of various market segments, such as achieving even finer lines to support further reductions in the cost of ownership of multi-crystalline cells with high RSheet LDEs.

Applications: Monocrystalline wafers with contact emitters having low phosphorus surface concentration for LDE cells.

Platform: Solamet PV17A photovoltaic metallisation front-side paste is a highly conductive silver composition, part of the DuPont Solamet PV17x family, designed to provide improved efficiency, reliable soldered adhesion and low lay-down. This paste may be co-fired with back-side (p-type) aluminium conductors, such as DuPont SolametPV3xx and DuPont SolametPV5xx tabbing silvers.

Availability: September 2012 onwards.

Isra Solar Vision



SOLARSCAN-YIELDMASTER PL from Isra provides high throughput inspection

Product outline: Isra Solar Vision's new 'SOLARSCAN-YIELDMASTER PL' is claimed to provide the industry's fastest contactless photoluminescence inspection with the lowest false detection rates and the most accurate defect classification for the mass production of solar cells.

Problem: The ability to characterize solar elements in mass production and provide a reliable distinction between material defects (such as dislocations, changes in the material, or foreign objects in the silicon) and process defects (cracks, finger interruptions, low efficiency regions, scratches, for example) to improve yield and overall improved productivity.

Solution: The new generation of high-speed, in-line YIELDMASTER PL inspection systems are claimed to offer the industry's best detection performance owing to the ability to detect and classify a large spectrum of attributes including, but not limited to, visible and invisible cracks, breaks, shunts, finger interruptions and leakage of electricity, series resistances, dark and inactive regions, black edging, firing defects, dislocations, grain boundaries, clusters, hot spots, scratches, broken pieces, pollution and material defects on solar cells and wafers. The homogeneous illumination of the complete field up to 170x170mm guarantees numerous advantages in comparison to EL (such as high intensities near busbars, dark corners and dark edges) and conventional PL inspection systems. More than 3,600 solar cells per hour can be inspected, resulting in substantial time and cost savings.

Applications: The modular system can be used for both solar cells and solar wafers.

Platform: The modular architecture of the new electroluminescence system allows the integration into new or existing production lines and fulfils varying inspection requirements for solar cells and wafers.

Availability: September 2012 onwards.

Development of $POCl_3$ emitters which enable Ag reduction while increasing solar cell efficiency: Assessing the impact on manufacturing and system costs

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ABSTRACT

The market price of Ag has fluctuated considerably over the past ten years and has impacted the manufacturing cost of Si solar cells and the price of Si PV. Reducing Ag consumption can decrease this cost; however, such reduction may come at the expense of cell performance. In order to address the issue of Ag cost reduction while maintaining high cell efficiency, phosphorus emitter profiles are tailored via $POCl_3$ diffusion to create solar cell emitters displaying low saturation current density (J_{0e}), variable electrically active surface phosphorus concentration ([$P_{surface}$]), and variable sheet resistance with the aim of reducing Ag consumption. By optimizing emitter diffusion conditions, it is possible to reduce screen-printed Ag paste consumption by 33% with no loss in cell performance. Using a screen-printable Ag conductor paste designed to contact low [$P_{surface}$] emitters, the performance of cells with screen-printed Ag paste dry masses of 200, 120 and 80mg is compared. By using a tailored low-J_{0e} 55Ω/sq emitter, it is possible to achieve a high open-circuit voltage (V_{oc}) and short-circuit current (J_{sc}) to yield average cell efficiencies of 18.64% and 18.73% for 120mg and 80mg Ag paste dry mass, respectively. This is compared with efficiencies of 18.52% for cells using state-of-the-art technology (industrial high [$P_{surface}$] 65Ω/sq emitter with 120mg Ag paste dry mass). On the basis of a Ag market price of US$32/troy oz and an 85% by weight thick-film paste Ag metal content, a Ag front-side metallization cost of US¢2.11/W can be achieved by using 80mg Ag paste dry mass, which translates to a Ag cost saving of US$5.4M per year for a 500MW production line when compared with the Ag cost for state-of-the-art technology. Further cost analysis shows a 1.2% area-related balance of system (BOS) cost reduction and a US¢0.1/kWh reduction when comparing low-J_{0e} 55Ω/sq modules and state-of-the-art modules. Calculations show that an additional 0.5% absolute efficiency for state-of-the-art modules is required, to compensate the efficiency gains and Ag cost reduction afforded by low-J_{0e} 55Ω/sq modules.

Introduction

For the PV industry to attain grid parity and reach a place of sustainability, installed system efficiency must increase while installed system cost must decrease. The US Department of Energy has mandated significant cost reductions in order for PV to become and remain cost-competitive with traditional energy sources [1]. In addition to streamlining BOS costs and soft costs associated with electrical permitting and consumer financing, module- and cell-level improvements will impact the efficiency and cost of the final system. Numerous organizations have published cell-level improvements indicating the potential for high efficiency. However, many improvements come with additional processing steps and materials which, because of added capital expense, tend to negate potential gains.

Figure 1. Market price of Ag from January 1975 to August 2012 in US$ per troy oz. Lowest price was $3.56/oz in March 1993; highest prices were $49.45/oz in January 1980 and $48.70/oz in April 2011 [2].

> "Contact metallization is one of the most expensive parts of Si solar cell fabrication."

Contact metallization is one of the most expensive steps in Si solar cell fabrication, since a majority of cells receive screen-printed thick-film Ag for the front-side collection grid. Over the past 40 years (see Fig. 1 [2]), the market price of Ag has seen dramatic shifts due to events like the Hunt brothers market-cornering scandal of 1980, as well as recent interest in Ag as an investment tool and the emergence of

Ag exchange-traded funds (ETFs) [3]. In the last ten years alone, the market price of Ag has fluctuated between \$5 and \$49 per troy ounce, ultimately impacting the manufacturing cost of Si solar cells and the price of c-Si PV. Although Ag price has fallen from its recent peak in April 2011, in order to reduce the cost of solar electricity generated by c-Si PV, the amount of Ag per cell needs to be reduced. The International Technology Roadmap for Photovoltaics (ITRPV) predicts that Ag consumption at the cell level will fall to 50mg by 2017 with the assumption that a transformative, manufacturable Cu-based metallization technology will be implemented by 2015 [4]. However, since Ag is the primary conductor involved in minority-carrier collection, simply reducing Ag consumption may result in the loss of cell performance due to degradation of fill factor (*FF*) and increased series resistance (R_{series}). Much effort has gone into research and development of metallization alternatives to Ag, such as Ni plating for the formation of Ni silicide contacts [5–6] as well as Cu plating and screen printing [7–11].

In addition to costs being lowered through a reduction in material consumption, solar cell performance must continue to rise in parallel. One potential route to achieving high efficiency is the use of lightly doped, low [$P_{surface}$] n^+ emitters on p-type wafers. Lightly doped emitters are recognized for the potential for higher V_{oc} and J_{sc}, through lower J_{0e} and higher short-wavelength response, respectively [12]. Low [$P_{surface}$] emitters have been studied and produced by novel methods [13,14]; however, contacting such emitters with conventional screen-printed thick-film Ag pastes is challenging and leads to very high Ag/Si contact resistance and high R_{series}. Poor contact to lightly doped emitters using thick-film Ag pastes is most likely due to the insufficient formation of current-transport structures/pathways at the Ag/Si contact interface and/or the formation of insulating interfacial glass layers, both of which prevent an efficient transfer of minority carriers from the bulk Si to the Ag collection grid.

Recently, using standard $POCl_3$ diffusion processes, Cooper et al. [15] demonstrated homogeneous n^+ emitters showing low J_{0e} and low [$P_{surface}$] that displayed low contact resistance using a screen-printable Ag conductor paste [16] specifically tailored to contact low [$P_{surface}$] emitters. Low-milliohm Ag/Si-specific contact resistance values were observed for solar cells with emitter active [$P_{surface}$] as low as 9E19cm^{-3}, and final V_{oc} values as high as 637mV were achieved on a relatively low emitter sheet resistance of 65Ω/sq.

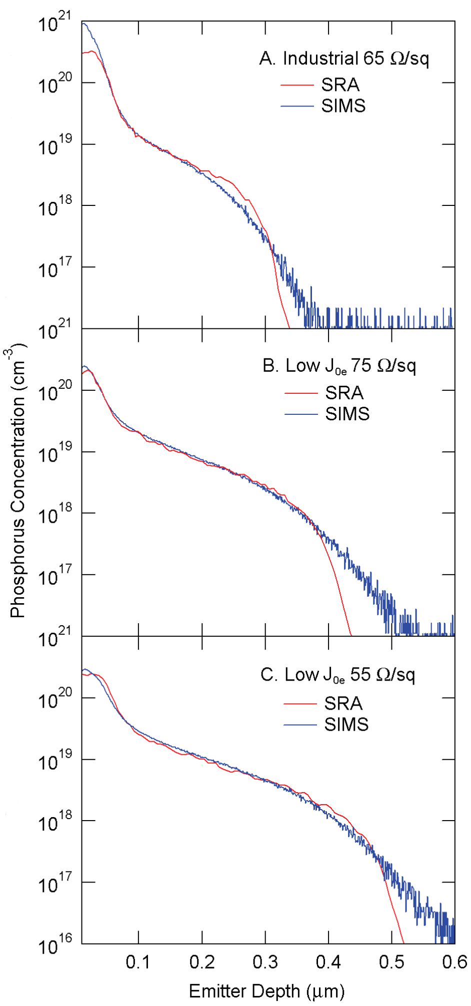

Figure 2. Spreading resistance (SRA) and secondary ion mass spectrometry (SIMS) profiles for: (A) industrial 65Ω/sq; (B) low-J_{0e} 75Ω/sq; and (C) low-J_{0e} 55Ω/sq emitters.

> "To address the problem of excess Ag consumption, the emitter sheet resistance is reduced while maintaining high emitter quality."

To address the problem of excess Ag consumption, contrary to conventional wisdom, the emitter sheet resistance is reduced while maintaining high emitter quality, as indicated by J_{0e}, implied V_{oc} and final V_{oc} measurements. The reduction in sheet resistance allows lower gridline pitch for the standard three-busbar H pattern (65 gridlines reduced to 50 gridlines). The reduction in gridline pitch in combination with narrower gridlines (>100µm reduced to 75–85µm) results in ~0.2% higher average cell efficiencies while decreasing Ag consumption by 33% as compared with the industry state of the art. Using the average solar cell efficiency/paste mass combinations presented, we speculate on what impact such a Ag reduction and an efficiency increase will have on system costs.

Cell fabrication and characterization

Large area (239cm^2) n^+-p-p^+ Si solar cells were fabricated on 1–3Ωcm B-doped Cz Si wafers of thickness 180–200µm. All wafers were anisotropically textured via KOH/isopropanol solution to attain quadrilateral pyramid size in the range of 3 to 7µm. n^+-p junctions were formed by $POCl_3$ tube diffusion in a Centrotherm furnace. Emitter sheet resistance and diffusion profile were manipulated by varying the time, temperature, $POCl_3$ bubbler N_2 flow rate, and O_2 flow rate of the furnace during diffusion. Following chemical edge isolation and phosphosilicate glass (PSG) removal, emitters were sunny-side coated with a SiN_x anti-reflective coating using a Centrotherm PECVD reactor. All wafers were screen printed via a semi-automated ASYS printer with DuPont Solamet PV17F to form the three-busbar H grid patterns. Ag screen printing was controlled to deliver 200 and 120mg dry paste mass, forming 65 gridlines, and 80mg dry paste mass, forming 50 gridlines. Commercially

available Al and Ag/Al pastes were screen printed on the rear side of all wafers for the formation of an Al back-surface field (Al-BSF) and rear tabbing stripes, respectively. After each screen-printing event, wafers were dried at 175°C in an IR belt furnace for one minute and fired in a seven-zone IR belt furnace from TPSolar.

A Sinton WCT-120 Photoconductance Lifetime Tester was used to estimate J_{0e} and implied V_{oc} for each emitter via quasi-steady state photoconductance decay (QSSPCD). Representative samples for J_{0e} and implied V_{oc} measurement were SiN_x coated on both sides after PSG removal and subjected to simulated contact firing. J_{0e} and implied V_{oc} values are reported at one-sun illumination (1.6–6.7E14 carriers/cm^2 injection level). J_{0e} is calculated from total J_0 ($J_0 = J_{sc}/e^{(\text{imp } V_{oc} \bullet q/k \bullet T)}$, where J_{sc} = 37.3mA/cm^2) by subtracting the bulk contribution ($J_{0b} = qn_i^2W/N_A\tau_{bulk}$, where q is the fundamental charge, n_i is the intrinsic carrier concentration, W is the wafer thickness, N_A is the base dopant concentration, and τ_{bulk} is the minority carrier lifetime of the wafer) and dividing the result by two since J_{0e} samples are two-sided symmetric structures [17]. Emitter doping profiles were measured via spreading resistance analysis (SRA) by Solecon Laboratories, Inc., and by secondary ion mass spectrometry (SIMS) at the National Renewable Energy Laboratory. Profile wafers were mirror polished and of a light base doping (15–20Ωcm resistivity) to allow [$P_{surface}$] and n$^+$-p metallurgical junction depth to be accurately established. Profile wafers were diffused in the centre of a full Cz wafer diffusion to simulate tube-packing conditions.

Comparison of industry state-of-the-art and low-J_{0e} emitters and solar cells

A series of n$^+$ emitters displaying low J_{0e} and variable [$P_{surface}$] were recently introduced in order to study the limits of low-resistance Ag thick-film contact [15]. In an extension of that study, the $POCl_3$ diffusion parameters were further refined, to create emitters with low [$P_{surface}$] and low J_{0e} while keeping sheet resistance low. Starting from diffusion conditions which resulted in a 75Ω/sq emitter with low J_{0e} and low [$P_{surface}$], the diffusion parameters were tuned to lower the sheet resistance to 55Ω/sq without a penalty in J_{0e}.

For comparison, this study includes a high [$P_{surface}$] 65Ω/sq emitter, which can be considered an industrial emitter easily contacted by most commercially available thick-film Ag pastes. Fig. 2 shows the dopant profiles for the industrial emitter (Fig. 2A) and two experimental emitters (Figs. 2B and 2C) used in the current study. Clear differences can be seen in [$P_{surface}$], in the depth of high [$P_{surface}$] near the wafer surface, and in the n$^+$-p junction depth when comparing industrial 65Ω/sq (Fig. 2A), low-J_{0e} 75Ω/sq (Fig. 2B) and low-J_{0e} 55Ω/sq (Fig. 2C) dopant profiles. In Fig. 2, electrically active [P] (red curve; SRA) and total [P] (blue curve; SIMS) are compared for each emitter. Samples for SRA and SIMS measurements were chipped from adjacent positions at the centre of profile wafers post-diffusion. A comparison of SRA and SIMS curves for the two experimental emitters reveals strong similarities as expected. However, the curves diverge sharply for the industrial 65Ω/sq emitter between 0 and 40nm depth. This divergence is accounted for by the substantial inactive P or 'dead layer' associated with the industrial emitter. Comparison of SRA and SIMS curves for the two experimental emitters show little or no inactive P.

Emitter	Active [$P_{surface}$] [atoms/cm^3]	n$^+$-p junction depth* [µm]	Implied V_{oc}** [mV]	J_{0e}** [fA/cm^2]
Industrial 65Ω/sq	3.5E20	0.33	631	394
Low J_{0e} 75Ω/sq	1.4E20	0.44	654	120
Low J_{0e} 55Ω/sq	2.5E20	0.52	652	149

* Based on device resistivity

** Implied V_{oc} and J_{0e} values derived from QSSPCD measurements

Table 1. Average physical and electrical characteristics of industrial and low-J_{0e} emitters.

Table 1 shows active [$P_{surface}$], n$^+$-p metallurgical junction depths based on device wafer resistivity, average implied V_{oc} and average J_{0e} for each emitter. Through emitter diffusion parameter tailoring, it was possible to achieve low J_{0e} and high implied V_{oc} values while decreasing emitter sheet resistance to 55Ω/sq, allowing flexibility in the Ag gridline pitch and total Ag consumption. The low J_{0e} value of 149fA/cm^2 observed for low-J_{0e} 55Ω/sq compared to 394fA/cm^2 for industrial 65Ω/sq is most likely due to the negligible inactive P layer found in low J_{0e} 55Ω/sq. A substantial 'dead layer', like that found in industrial 65Ω/sq, can lead to the formation of crystal defects and precipitates [17], thus degrading J_{0e}. Indeed, it is speculated that the decrease in precipitates associated with 'dead layer' elimination leads to a reduction in Shockley-Read-Hall recombination in the emitter, increased emitter minority-carrier lifetime, and improved surface passivation potential via applied dielectric layers [18].

It is possible to derive surface recombination velocities (SRV) associated with the emitters used in this study through internal quantum efficiency (IQE) curve fitting using PC1D solar cell modelling software [19]. Details for the specific PC1D input parameters used for SRV extraction can be found in Cooper et al. [15]. The short-wavelength region of solar cell IQE (300–600nm) is influenced by emitter quality. PC1D fitting of this region, with specific experimental external reflectance and SRA profile inputs for each emitter, produced SRV values of 1.2E5cm/s for industrial 65Ω/sq and 3.5E4cm/s for both low J_{0e} 75Ω/sq and low J_{0e} 55Ω/sq. In agreement with measured J_{0e} and implied V_{oc} values, a comparison of industrial 65Ω/sq with low J_{0e} 55Ω/sq reveals more than a factor of two difference in surface recombination, despite the similarity in sheet resistance.

Table 2 shows average light *I-V* performance for solar cells fabricated with the three emitters studied above and the three Ag paste dry masses used for front-side H grid pattern formation. Focusing first on the largest Ag paste mass (200mg), the average *FF* is greater than 0.79 for solar cells with each emitter. Previous specific contact resistance analysis of similar emitters showed contact resistance values ranging from 2 to 5mΩcm^2 using a similar Ag conductor paste [15]. Such low contact resistance combined with full gridlines provided by 200mg Ag paste mass enables low R_{series}.

As Ag paste mass decreased by reducing the Ag lay-down and number of gridlines, a higher solar cell J_{sc}, by up to 1mA/cm^2, is seen, but also *FF* is lower and R_{series} is higher (Table 2). The fall in *FF* and the rise in R_{series}, observed as the Ag paste dry mass decreases, arise from lower Ag gridline conductivity due to narrower gridlines and greater gridline pitch as a result of using 50 gridlines as opposed to 65. Because of the lower *FF* and higher R_{series}, cells made with industrial 65Ω/sq and low-J_{0e} 75Ω/sq emitters show a loss in efficiency, despite an increase in J_{sc}, when Ag paste dry mass is reduced to 80mg. However, the maximum efficiency observed for solar cells with a low-J_{0e} 55Ω/sq emitter occurs for the lowest Ag paste dry mass (80mg).

"The true advantage of the low-J_{0e} emitters is the higher final V_{oc}."

It is important to note that the true advantage of the low-J_{0e} emitters is the higher final V_{oc}. Solar cells made with the

Emitter	Paste mass [mg] /gridline count	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF	η[%]	n factor	R_{series} [Ωcm^2]	R_{shunt} [Ωcm^2]
Industrial 65Ω/sq	200/65	630	36.8	0.793	18.35	1.06	0.53	4707
	120/65	630	37.3	0.789	18.52	1.03	0.69	5097
	80/50	630	37.7	0.767	18.21	1.02	1.10	5013
Low J_{0e} 75Ω/sq	200/65	637	37.0	0.791	18.63	1.07	0.62	4222
	120/65	639	37.6	0.788	18.90	1.05	0.72	5359
	80/50	637	37.8	0.771	18.58	1.05	1.05	6665
Low J_{0e} 55Ω/sq	200/65	635	36.6	0.798	18.53	1.07	0.49	5511
	120/65	635	37.2	0.790	18.64	1.05	0.68	4762
	80/50	635	37.6	0.784	18.73	1.03	0.81	4968

Table 2. Average light *I-V* characteristics of 239cm^2 solar cells fabricated on industrial and low-J_{0e} emitters.

low-J_{0e} 55Ω/sq emitter show a 5mV V_{oc} gain over cells made with the industrial 65Ω/sq emitter. This gain, combined with the higher *FF* that can be achieved because of a lower sheet resistance, enabled an average efficiency of 18.73% and a best efficiency of 18.89% to be realised using only 80mg Ag paste dry mass.

Impact of Ag reduction combined with higher efficiency on manufacturing and system cost

Given the extreme pressure on cell manufacturer profit margins these days, the cost of Ag consumption becomes a key figure of merit, provided cell efficiency remains comparable. Fig. 3 illustrates the US¢/W cost of Ag consumption for each emitter and Ag paste dry mass combination studied. Ag cost values are calculated from cell power output based on data in Table 2, US$32/troy oz Ag market price, and 85% by weight thick-film paste Ag metal content. Additional factors considered in the Ag cost calculation are 2% waste during cell manufacture and 90% cell yield. By comparing the Ag costs for 200 and 120mg Ag paste dry masses, it is seen that solar cells with a low-J_{0e} 75Ω/sq emitter show a slight advantage owing to the higher power output. However, the advantage shifts to solar cells with a low-J_{0e} 55Ω/sq emitter when 80mg Ag paste dry mass is used. Ag cost drops from US¢3.13/W for the 75Ω/sq emitter with 120mg Ag paste dry mass, to US¢2.11/W for the 55Ω/sq emitter with 80mg Ag paste dry mass.

Ag market price volatility was illustrated in the introductory section of this paper. With potential Ag prices ranging from US$4/troy oz to US$50/troy oz, Table 3 explores the impact of Ag market price on the cost of Ag for manufacturing solar cells with a low-J_{0e} 55Ω/sq emitter + 80mg Ag paste dry mass (η_{avg} = 18.73%), as well as for cells with an industrial 65Ω/sq emitter + 120mg Ag paste dry mass (η_{avg} = 18.52%). In the case of a 500mW production line, yearly Ag cost for cells made with a low-J_{0e} 55Ω/sq emitter + 80mg Ag paste dry mass range from US$2.8M to US$15.5M

Ag market price [US$/troy oz]	Ag cost: low J_{0e} 55Ω/sq + 80mg [$M]	Ag cost: industrial 65Ω/sq + 120mg [$M]	Ag cost savings/yr* [$M]
4	2.8	4.2	1.4
10	4.4	6.7	2.2
25	8.6	13.0	4.4
32	10.5	15.9	5.4
50	15.5	23.5	8.0

* $\text{cost}_{(\text{industrial } 65\Omega/\text{sq} + 120\text{mg})} - \text{cost}_{(\text{low J0e } 55\Omega/\text{sq} + 80\text{mg})}$

Table 3. Potential cost savings per year for a 500MW production line at various Ag market prices.

within the market price range given. At US$32/troy oz, the cost advantage for cells made with a low-J_{0e} 55Ω/sq emitter + 80mg Ag paste dry mass translates to a saving of US$5.4M per year over cells made with state-of-the-art industrial 65Ω/sq + 120mg Ag paste dry mass – in other words, a saving of ~33%. Comparison of Ag cost for these two emitter/paste mass combinations is appropriate, since the current industry state of the art is 120mg Ag paste dry mass on high [$P_{surface}$] emitters.

The cost analysis can be extended by observing the impact of the combined Ag reduction and cell efficiency gains observed here on system cost. For this analysis, the industry state-of-the-art cells (η_{avg} = 18.52% with 120mg Ag paste dry mass) and the low-J_{0e} 55Ω/sq cells (η_{avg} = 18.73% with 80mg Ag paste dry mass) are compared. First, average cell efficiencies are converted to module efficiency and corresponding module power. Since one module (area = 1.635m^2) is fabricated from sixty 239cm^2 cells, and the Cz wafers used are pseudo-square, the ratio of cell to module area is 0.877 (1.434m^2/1.635m^2). With cell to module power loss of 4%, the state-of-the-art module efficiency and power are 15.56% and 254.4W, respectively, and the low-J_{0e} 55Ω/sq module efficiency and power are 15.73% and 257.2W, respectively.

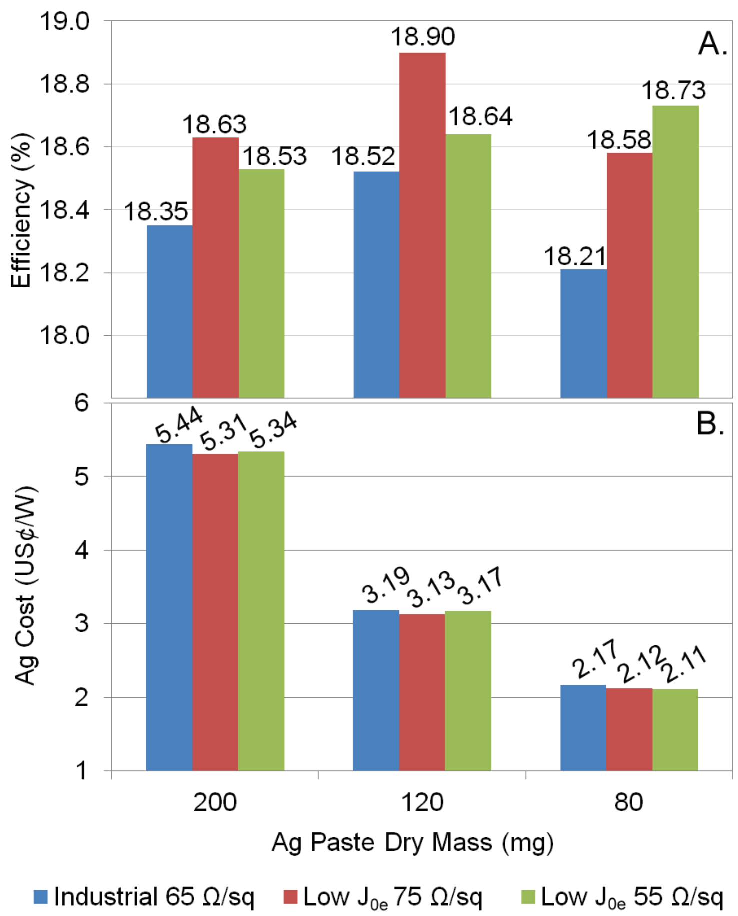

Figure 3. Average efficiency (%) and the cost (US¢/W) for front-side Ag consumption as a function of Ag paste dry mass. Calculation is based on US$32/troy oz Ag market price, 85% by weight paste Ag content, and additional factors.

The 0.2% absolute efficiency improvement observed for modules with cells having the low-J_{0e} 55Ω/sq emitter + 80mg Ag paste dry mass combination will lead to a reduction in area-related BOS costs since fewer modules will be needed for a common power output. (Area-related BOS takes into account installation labour, mounting hardware, support structures, interconnections, wiring and land required during PV system installation.) In general, the higher efficiencies achieved with low-J_{0e} 55Ω/sq modules results in area-related BOS costs that are 1.2% lower, representing a saving of US¢1.10/W [20].

> "As the Ag market price changes, the required additional state-of-the-art module efficiency also changes."

To quantify the impact of Ag reduction, it is possible to calculate the additional absolute module efficiency required for a state-of-the-art module to compensate the Ag cost savings that are realized by using a low-J_{0e} 55Ω/sq module [20]. The effect of Ag cost reduction is decoupled by assuming equal module power for the two compared technologies, and determining the additional module efficiency needed to cancel the Ag cost savings. Assuming a module price of US$0.70/W, in order to maintain the same module manufacturing cost the state-of-the-art module would need a 0.25% absolute higher efficiency to compete with the Ag cost savings afforded by low-J_{0e} 55Ω/sq modules at the US$32/troy oz Ag market price. Fig. 4 shows that, as the Ag market price changes, the required additional state-of-the-art module efficiency also changes. It is interesting to note that, at US$50/troy oz Ag market price, an absolute efficiency enhancement of up to 0.4% would be required for state-of-the-art modules to equal the cost of low-J_{0e} 55Ω/sq modules. The results of this analysis, combined with the 0.2% absolute efficiency gain afforded by low-J_{0e} 55Ω/sq modules, indicates that state-of-the-art modules would require a 0.5% absolute higher efficiency in order to compensate these gains and for both module types to be equal in price.

> "By optimizing emitter diffusion conditions, it was possible to reduce screen-printed Ag paste consumption by 33%, with no loss in cell performance."

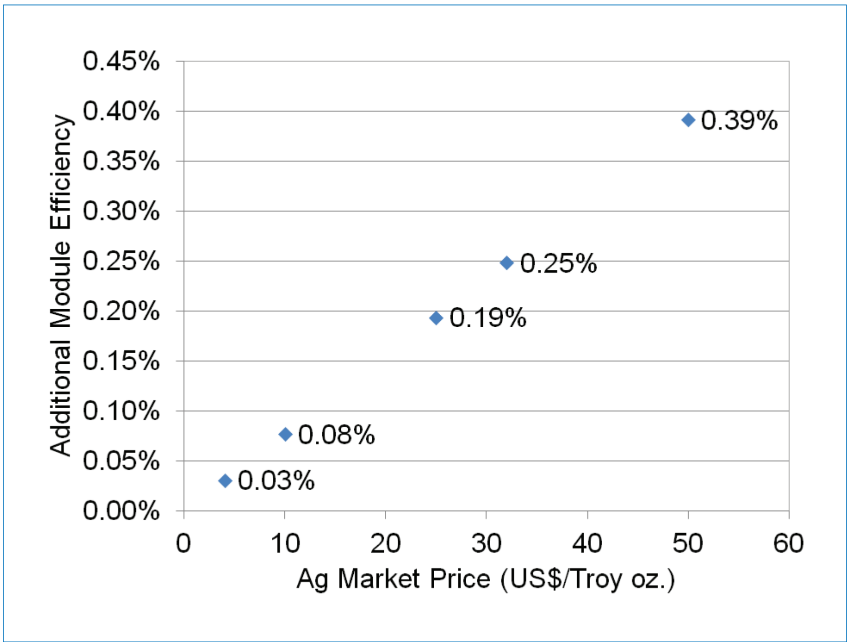

Figure 4. Additional state-of-the-art module efficiency required to offset low-J_{0e} 55Ω/sq module Ag cost savings as a function of Ag market price.

Summary

In order to address the issue of reducing the cost of Ag usage at the same time as maintaining high cell efficiency, phosphorus emitter profiles were tailored via $POCl_3$ diffusion to create solar cell emitters displaying low J_{0e} and low [$P_{surface}$] while minimizing sheet resistance with the aim of reducing Ag consumption. By optimizing emitter diffusion conditions, it was possible to reduce screen-printed Ag paste consumption by 33%, with no loss in cell performance. A screen-printable Ag conductor paste designed to contact low [$P_{surface}$] emitters was used, and the performance of cells with screen-printed Ag paste dry masses of 200, 120 and 80mg was compared. By using tailored low-J_{0e} 55Ω/sq emitters, higher values of V_{oc} and J_{sc} were able to maintain or increase average efficiencies to 18.64% and 18.73% for cells with 80mg and 120mg Ag paste dry weight, respectively. In comparison, an average efficiency of 18.52% was achievable for cells made using state-of-the-art technology (industrial high [$P_{surface}$] emitter with 120mg Ag paste dry mass). On the basis of a Ag market price of USD$32/troy oz and thick-film paste Ag metal content of 85%, a Ag front-side metallization cost of US¢2.11/W can be realized by using 80mg Ag paste dry mass. This figure represents cost savings of 33% and 60%, respectively when compared with Ag costs of US¢3.19/W and US¢5.44/W for traditional, industrial-type emitters using 120–200mg Ag paste dry mass. Further analysis shows that area-related BOS costs for low-J_{0e} 55Ω/sq modules will be 1.2% lower (owing to higher power output) than for state-of-the-art modules. Calculations show that an absolute module efficiency of 0.25% is required for state-of-the-art modules to offset the Ag cost reduction afforded by low-J_{0e} 55Ω/sq modules at current Ag market prices. Finally, in order for state-of-the-art technology to compensate the combination of 0.2% absolute efficiency gain and Ag cost reduction afforded by the low-J_{0e} 55Ω/sq technology, an absolute efficiency enhancement of 0.5% would be required.

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Back-contacted high-efficiency silicon solar cells – conversion efficiency dependence on cell thickness

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ABSTRACT
Reducing the cost of photovoltaic energy is the main objective of solar cell manufacturers. This is ideally realized by increasing cell efficiency and simultaneously decreasing manufacturing cost. To reduce fabrication costs, the international roadmap of photovoltaics (ITRPV) forecasts a reduction in cell thickness from 180µm to 120µm in the next six years, and even thinner cells may be desirable, as long as efficiency and yield are not negatively affected. In order to increase efficiency, the ITRPV forecasts an increase in share of back-contacted cells from 5% to 35% in the next eight years. In this paper the dependence of the efficiency of back-junction back-contact (BJBC) solar cells on cell thickness is investigated experimentally and numerically. To this end, BJBC silicon solar cells with cell thicknesses ranging from 45µm to 290µm are fabricated and simulated. Thinned float-zone material is used as well as monocrystalline epitaxial layers fabricated by the porous silicon process for 45µm-thick cells. The efficiency of the best cell is 22.6% (130µm cell thickness) and 18.9% for an epitaxial cell (45µm thickness). Loss mechanisms in the maximum power point of all cells are investigated by using a free-energy loss analysis based on finite-element simulations. A lower generation and a lower recombination in thinner cells compete against each other, resulting in a maximum efficiency of 20% for a cell thickness of 45µm at a base lifetime of 20µs. At a base lifetime of 3000µs, the maximum efficiency is greater than 23% for a cell thickness beyond 290µm, but reducing the cell thickness from 290µm to about 90µm results in a power loss of less than 0.6% absolute.

Introduction
Back-junction back-contact (BJBC) silicon solar cells combine a high conversion efficiency potential with a single-side cell interconnection within the module [1,2]. The advantages of the single-side cell interconnection are the reduction of handling steps [3] and the avoidance of micro-cracks by using a conductive foil [4]. By using high-throughput processes, such as ion implantation [5,6] and laser processing [7], the back-junction process may in the future reduce fabrication costs compared to the standard screen-printed solar cell process. Furthermore, the decrease in material consumption also leads to a reduction in costs.

The effect of cell thickness on solar cell efficiency has already been studied for solar cells with two-sided contacts. In 1982 Chih-Tang et al. [8], using low base lifetime material, determined a broad efficiency peak of 17% at around 50µm cell thickness. Kray et al. [9] found that efficiency is practically independent of cell thickness for Czochralski-grown material, and efficiency only slightly increases by up to 1% absolute with increasing cell thickness from 36µm to 250µm for float-zone material. In the latter study, silicon wafers with an initial thickness of 250µm were thinned down by an infeed grinder to achieve the desired thickness. However, for production this technique is obviously not feasible.

> “The highest solar cell conversion efficiency achieved using the latest kerf-less technologies is only 15%, whereas a 19.1% conversion efficiency has been obtained by applying the PSI process.”

For this investigation, the porous silicon process (PSI) [10,11], which was first discovered in 1997, is used to fabricate 45µm-thick crystalline silicon films. This technology skips the wafering process, in which 55% of the material is wasted (at a current wafer thickness of 180µm). Alternatives to this technique include the separation of a thin silicon film from a monocrystalline substrate wafer by annealing a stack of metal deposited on top of a silicon wafer and by using ion implantation [12,13].

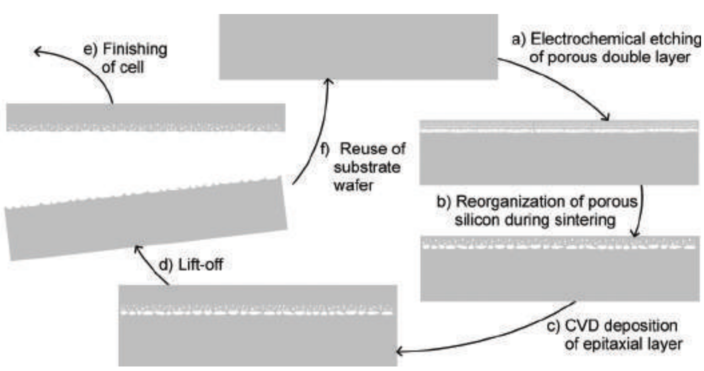

Figure 1. Schematic of the porous silicon process: (a) a porous double layer is electrochemically etched in a substrate wafer – the bottom layer has a high porosity, whereas the upper layer has a low porosity; (b) the porous double layer reorganizes during a sintering step in hydrogen at 1100°C; (c) an epitaxial Si layer grows in a chemical vapour deposition (CVD) at 1100°C; (d) the epitaxial layer is lifted off – the high porosity layer serves as the breaking point; (e) the epitaxial solar cell can be finished; (f) the substrate wafer can be reused for the next PSI cycle.

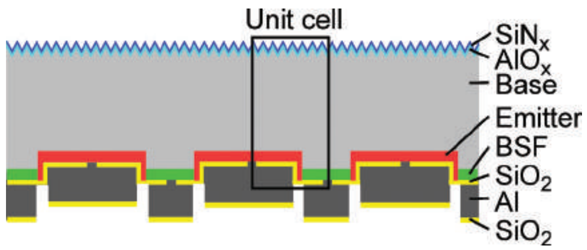

Figure 2. Schematic cross section of the BJBC solar cell (not to scale) – the cross section of the unit cell is indicated by a box. (Adapted from Haase et al. [19].)

However, the highest solar cell conversion efficiency achieved using the latest kerf-less technologies is only 15% [14], whereas a 19.1% conversion efficiency has been obtained by applying the PSI process [15]. To examine the entire thickness range between 45µm and 290µm, thinned float-zone silicon samples are also used.

Fabrication of BJBC solar cells

Float-zone material thinned by wet-chemical etching was used, as well as monocrystalline thin films fabricated by PSI. In this process a porous double layer is etched electrochemically into the surface of a thick silicon wafer, as shown in Fig. 1. After sintering at 1100°C in a hydrogen atmosphere, silicon is grown epitaxially on top of the closed surface of the top porous silicon layer. The growth process controls the layer thickness as well as the doping gradients. Finally, the highly porous bottom layer permits a lifting-off of the epitaxial silicon layer, and a solar cell is then processed from the thin layer. The thick silicon substrate wafer can be reused for many more PSI cycles [16,17]. The material consumption is much lower, since only the porous layer of 2µm is lost in comparison to sawing losses of 120µm.

The cell-thickness dependence of the efficiency will be illustrated by means of BJBC solar cells fabricated with a cell size of 3.92cm^2; all the cells are processed in a single batch for better comparison of the results. A cell process previously developed at ISFH [18] is employed, which uses industrially feasible laser processes and avoids laboratory processes such as photolithography.

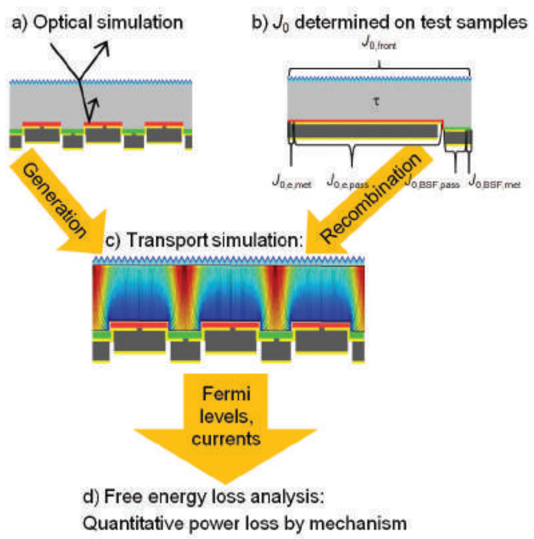

Figure 3. Loss analysis procedure. A simulated generation profile and the saturation current densities determined for test samples are input parameters for the finite-element simulation. Output parameters such as Fermi levels and currents are used for the free-energy loss analysis.

Group	130-1.5	290-1.5		290-0.5		90-0.5		45-0.5	
Cell thickness d [µm]	130	290		290		90		45	
Base resistivity ρ [Ωcm]	1.5	1.5		0.5		0.5		0.5	
Base lifetime τ [µs]	4000	4000		3000		3000		20	
Number of processed cells	1	6		8		12		3	
	best	best	6 best	best	6 best	best	6 best	best	3 best
Open circuit voltage V_{oc} [mV]	671	672	672	673	673	672	669	651*	653
Short circuit current density J_{sc} [mA·cm^{-2}]	41.1	40.9	40.6	39.7	39.2	38.4	37.5	36.0*	35.3
Fill factor FF [%]	81.8	81.9	80.2	81.6	81.3	81.9	80.2	80.6*	79.8
Conversion efficiency η [%]	22.6	22.5	21.9	21.8	21.4	21.1	20.1	18.9*	18.4
$\Delta\eta$ caused by difference in:	cell thickness			cell thickness					
$\Delta\eta$ caused by difference in:		base resistivity and lifetime				base lifetime and cell thickness			

*independently confirmed by Fraunhofer ISE

Table 1. Material properties and parameters of the light *J-V* curves of the five groups investigated in this study. The best cell is shown, as are the average values of the six best cells and of the three best cells.

The cell structure is shown in Fig. 2. The front surface is textured and a 10nm-thick AlO_x passivation layer is deposited by atomic layer deposition. A SiN_x layer serves as an anti-reflection coating. The rear side is processed as an interdigitated finger structure with an index of 1mm. The phosphorous emitter with a sheet resistance of 70Ω/sq covers 84% of the cell rear side. A boron-diffused back-surface field (BSF) with a sheet resistance of 20Ω/sq reduces the recombination rate beneath the contacts. A thermal oxide of thickness 150nm serves as a rear-side passivation and rear reflector. Laser contact opening (LCO) of the passivation layer and subsequent aluminium evaporation form the contacts. This 10µm-thick aluminium layer is etched at the edges separating the emitter and the BSF layer [20].

Five different groups of cells – categorized according to cell thickness and base resistivity – were investigated. Table 1 shows the material properties and parameters of the light *J-V* curves of the processed groups. Cell thicknesses varied from 45µm to 290µm, base resistivities from 1.5Ωcm to 0.5Ωcm and base lifetimes from 20µs to 4000µs.

Loss analysis of BJBC solar cells by means of device simulations

The loss mechanisms in the experimental devices are analyzed by determining the generation, recombination and transport losses. The generation is simulated using the ray tracer SUNRAYS [21]. Input parameters are measured geometries and optical layer properties. To determine the recombination at the surfaces, the Kane-Swanson method [22] is used, which is based on infrared lifetime measurements [23] on test samples that are processed in parallel to the solar cells. The saturation current densities of all passivated and metalized surfaces [24] are determined. The base lifetime is extracted by varying the thickness of these test samples [25].

As shown in Fig. 3 the generation profile from the SUNRAYS simulation (Fig. 3(a)) and the recombination parameters (Fig. 3(b)) are input parameters for a transport simulation (Fig. 3(c)). The transport simulation uses the conductive boundary (CoBo) model [26], which is implemented in the finite-element analyzer COMSOL [27]. The CoBo model treats diffused surfaces as one-dimensional boundaries characterized by a sheet resistance and a saturation current density. A free-energy loss analysis [28] based on the finite-element simulation yields the generated free-energy power densities lost by different mechanisms and extracted as shown in Fig. 3(d).

Fig. 4 shows the simulated power densities at the maximum power point of the five experimentally investigated groups, which are irradiated with an intensity of 1000Wm^{-2}: the generated and both the simulated and measured extracted power densities are plotted. The main power density losses and the sum of all losses are also shown. The extracted power densities of the simulations are about 10Wm^{-2} (corresponding to 1% efficiency points) higher than the measured values. This deviation is attributed to resistive losses at the contacts and in the metal grids (these losses are not implemented in our simulations).

Fig. 5 shows the local minority-carrier current paths; the colour quantifies the power density loss by Shockley-Read-

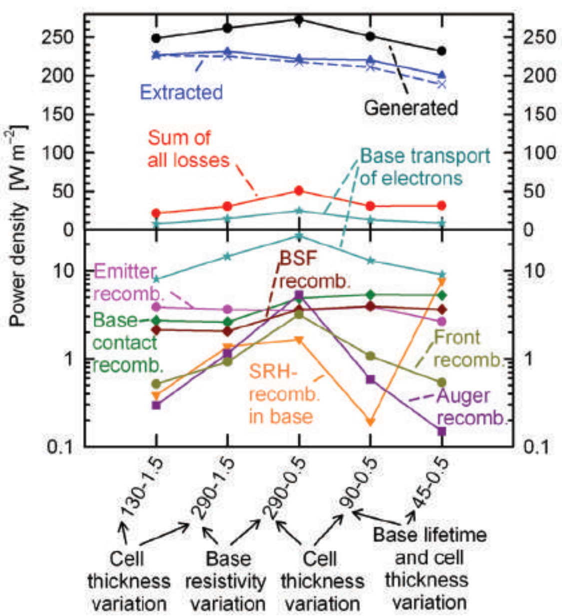

Figure 4. Power densities of unit cells of the five cell groups: simulated generated power densities and both simulated (solid line) and measured (dashed line) extracted power densities are shown. Also indicated are the main power density losses of the unit cells and the sum of these losses. (Adapted from Haase et al. [19].)

Hall (SRH) recombination of the five investigated groups. The minority-carrier current paths start very close to the front surface of the unit cell, and most of them end at the rear surface of the cell. The electrons which follow the paths to the emitter and are not lost by recombination are collected and contribute to the power output. The electrons which follow the other paths are all lost by recombination. The effect of the current paths ending at the rear surface of the base finger is called electrical shading [29]: this area is indicated by a black line on top of the cells.

The simulated impact of cell thickness, base doping and base lifetime on the conversion efficiency and on the local recombination and minority carrier current paths will be discussed next.

Impact of cell thickness on conversion efficiency

The thickness dependence is best analyzed by comparing the results of groups 290-0.5 and 90-0.5 or 290-1.5 and 130-1.5, which differ in thickness only, as shown in Table 1. At long wavelengths, the spectral response of thin cells is not as good as thick cells: the generated power density therefore decreases with decreasing cell thickness by 5% relative at a base resistivity of 1.5Ωcm and by 10% relative at a base resistivity of 0.5Ωcm.

The free-energy transport loss of electrons is the highest power density loss for all thickness values, but shows a strong decrease with decreasing cell thickness. The free-energy transport loss of electrons is a quadratic function of the electron quasi-Fermi level gradient. Since this gradient decreases with increasing distance to the emitter, the total electron transport loss F_{bt_e} increases with an exponent x of less than one with increasing distance to the emitter and thus with increasing cell thickness d ($F_{bt\_e} \sim d^x$, x<1).

All power density losses caused by recombination in the base (SRH recombination, Auger recombination) or at the front surface decrease with decreasing cell thickness. The SRH recombination increases with increasing distance to the emitter because of an increase in minority carrier concentration, illustrated by comparing Figs. 5(a) and 5(c) with Figs. 5(b) and 5(d) respectively. The bottom part of cell 290-0.5 shows nearly the same local SRH recombination as cell 90-0.5; a comparison of cell groups 290-1.5 and 130-1.5 indicates the same effect. This characteristic is due to the quasi-Fermi level gradient of the minorities that causes an increase in minority-carrier concentration with increasing distance to the emitter.

On the other hand, the power density losses caused by the rear surface (emitter recombination, BSF recombination and base contact recombination) increase only

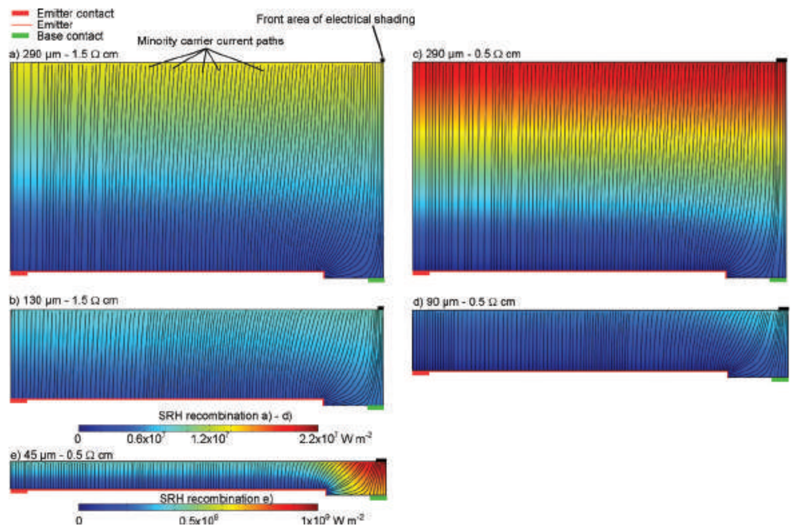

Figure 5. SRH recombination and minority-carrier current paths (black lines) of each unit cell. For comparison purposes the first four cells (a) to (d) are plotted on the same scale, whereas cell 45-0.5 has the highest SRH recombination and therefore uses a wider range. The regions of the contacts, emitter and electrical shading are shown for each cell. (Adapted from Haase et al. [19].)

slightly with decreasing cell thickness. The number of minority-carrier current paths which end in the base contact, where the electrons recombine, slightly increases with decreasing cell thickness. For these two reasons a low recombination at the base finger, and especially at the base contact, becomes more important for thinner cells.

> "Thinner cells benefit from lower front and base recombination, but at the same time suffer from a reduced generation."

In conclusion, thinner cells benefit from lower front and base recombination, but at the same time suffer from a reduced generation. Depending on the specific material properties, a decrease in cell thickness might thus result in either a decrease or an increase in cell efficiency. In the study presented here, decreasing the cell thickness from 290µm to 130µm for 1.5Ωcm and 4000µs material leads to a decrease in conversion efficiency of 0.5% absolute. However, decreasing the cell thickness from 290µm to 90µm for 0.5Ωcm and 3000µs material leads to a decrease in conversion efficiency of only 0.2% absolute.

Impact of base-doping on conversion efficiency

The base-doping dependence is analyzed by comparing the results of groups 290-1.5 and 290-0.5, which differ only in base doping, as shown in Table 1. The base lifetime of both samples does not differ significantly. The power densities are free energies and proportional to the quasi-Fermi level splitting. Decreasing the base resistivity and thus increasing the base-doping density lowers the Fermi level in p-type cells. This leads to an increase in quasi-Fermi level splitting, resulting in an increase in generated power density as well as in power density losses.

The transport loss of electrons is the highest power density loss for both doping densities and increases with increasing base doping. Since the quasi-Fermi level splitting in the base increases but is on the same level at the emitter, the gradient of the electron quasi-Fermi level increases with increasing base doping, which increases the free-energy loss by electron transport.

Auger recombination is proportional to ($n \times p^2$) at low-level injection in these p-type solar cells. For this reason, Auger recombination increases by a factor of about nine when base doping p increases by a factor of three, which is the case for a decrease in base resistivity from 1.5Ωcm to 0.5Ωcm.

Figs. 5(a) and 5(c) show that the loss by SRH recombination in cell 290-1.5 is 17% lower than in cell 290-0.5. The reason for this is a higher diffusion length and a lower quasi-Fermi level splitting in 290-1.5. Both cell groups, however, are not limited by this loss mechanism. The emitter recombination is the only loss mechanism which decreases with decreasing base resistivity. The electrical shading affects a larger part of the cell at a lower base resistivity (0.5Ωcm) than at a higher base resistivity (1.5Ωcm), as illustrated in Fig. 5.

All these effects lead to the conclusion that a base resistivity of 1.5Ωcm should be used instead of 0.5Ωcm, since the former results in decreased power losses by Auger, SRH and rear-surface recombination for a thickness of 290µm and a high base lifetime of 3000µs to 4000µs.

"A base resistivity of 1.5Ωcm should be used instead of 0.5Ωcm, since the former results in decreased power losses by Auger, SRH and rear-surface recombination."

Simulating the optimum conversion efficiency dependent on cell thickness, base doping and base lifetime

In order to evaluate a larger parameter space, a simulation study was carried out to analyze the impact on the solar cell conversion efficiency of base doping combined with cell thickness for different base lifetimes. The simulations are based on the same measured geometries and recombination parameters as those obtained for the experimental cells. Figs. 6 and 7 are valid for different base lifetimes of 20µs (measured on the epitaxial layer cell) and 3000µs (measured on the float-zone wafer cell). Both Figures show the solar cell conversion efficiency for doping densities of 10^{14}cm^{-3} to 10^{17}cm^{-3} and cell thicknesses of 18µm to 290µm. The arrows indicate how the different loss mechanisms influence the conversion efficiency.

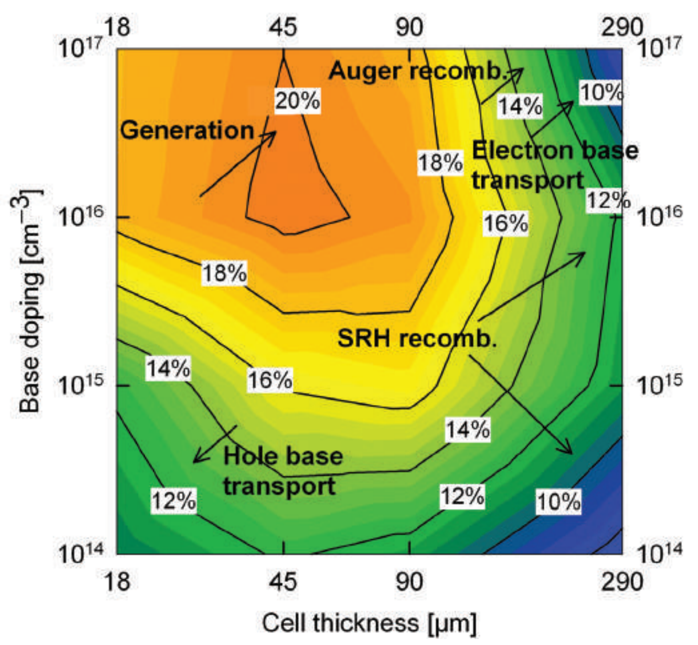

Figure 6. Solar cell conversion efficiency as a function of the base doping and cell thickness for a base lifetime of 20µs. The impact of the free energy of generation as well as loss mechanisms is indicated by arrows. (Adapted from Haase et al. [19].)

Fig. 6 shows the efficiency for a minority-carrier lifetime of 20µs. The efficiency decreases with decreasing cell thickness (lower generated free energy) and decreasing base doping. Resistive losses by majority carriers in the lateral direction also increase with decreasing cell thickness owing to an increased sheet resistance in the base. The sheet resistance also increases with decreasing base-doping concentration, which in turn decreases the conversion efficiency.

On the other hand, the transport of electrons increases with increasing cell thickness and base doping. The minority-carrier concentration increases with increasing cell thickness. This increase in carrier concentration increases SRH recombination, which decreases the efficiency. Auger recombination also increases with increasing cell thickness because of the quasi-Fermi level gradient to the front surface, which also decreases the efficiency. Auger recombination also increases quadratically with increasing base doping. For a base lifetime of 20µs, these are the main effects that lead to a maximum efficiency at a cell thickness of 45µm and a base-doping density between 10^{16}cm^{-3} and 10^{17}cm^{-3}.

Fig. 7 shows the efficiency for a minority carrier lifetime of 3000µs. For this lifetime the effect of SRH recombination is reduced compared to the 20µs lifetime, and the diffusion length does not significantly limit efficiency in the case of cell thicknesses up to 290µm. The efficiency presents a maximum for a base-doping concentration of about 10^{16}cm^{-3}. The limiting parameters for thin cells with a lifetime of 3000µs are the decreased generation and the base resistance losses. The maximum efficiency is greater than 23% for cell thicknesses above 290µm, but if the thickness is reduced from 290µm to about 90µm, the power loss is less than 0.6% absolute. The generation may be enhanced by improved light trapping, whereas the base resistance losses may be reduced by a highly doped

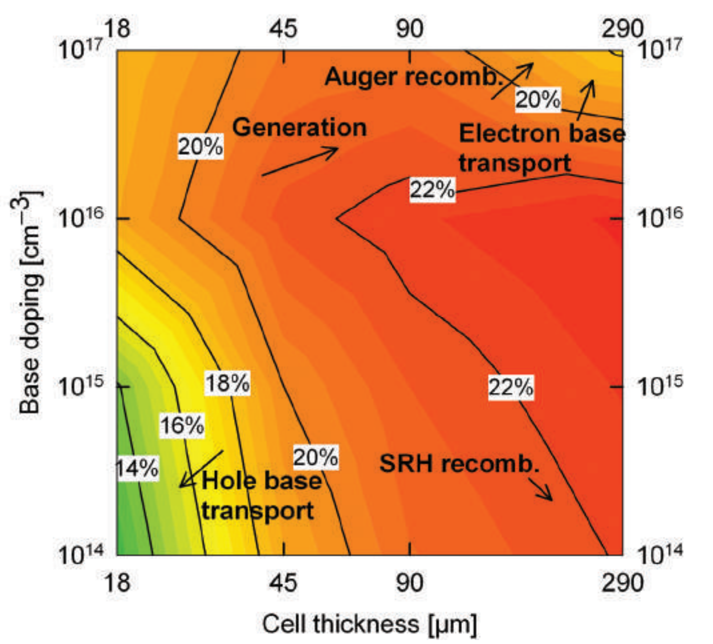

Figure 7. Solar cell conversion efficiency as a function of the base doping and cell thickness for a base lifetime of 3000µs. The impact of the free energy of generation as well as loss mechanisms is indicated by arrows. (Adapted from Haase et al. [19].)

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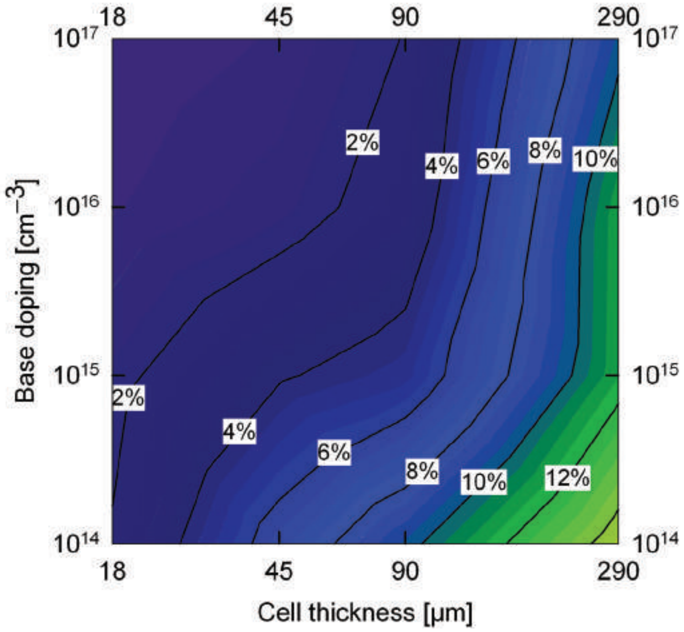

Figure 8. Difference between solar cell conversion efficiencies for base lifetimes of 3000µs and 20µs as a function of base doping and cell thickness.

layer (e.g. at the front surface), which deceases the base sheet resistance but does not significantly increase the recombination. Another possibility for reducing the resistance losses is to shorten the current path lengths by changing the geometry of the cell (e.g. smaller unit cells).

Fig. 8 shows the difference between solar cell conversion efficiencies for base lifetimes of 3000µs and 20µs. The difference in conversion efficiency is less than 1% absolute at doping densities of more than 10^{16}cm^{-3} and cell thicknesses of less than 45µm. At lower doping densities and higher cell thicknesses, the difference in efficiency increases to more than 14% absolute, which is mainly due to the increase in SRH recombination.

> "The highest efficiency of 22.6% was measured on a 130µm-thick, 1.5Ωcm-resistivity cell with a base lifetime of 4000µs."

Conclusion

The fabrication and analysis of high-efficiency BJBC cells has been demonstrated. The highest efficiency of 22.6% was measured on a 130µm-thick, 1.5Ωcm-resistivity cell with a base lifetime of 4000µs. A 290µm-thick cell with a resistivity of 1.5Ωcm showed almost the same efficiency (22.5%), since an increase in generation offsets any increase in front and base recombination. The simulation study, which is based on measured input parameters, showed the impact of the loss mechanisms on the conversion efficiency. The maximum efficiency shifts to a larger cell thickness, with increasing base lifetime for a BJBC cell. The maximum efficiency for a BJBC is around 10^{16}cm^{-3} base-doping density, since Auger recombination and transport losses by electrons increase with higher base-doping density, and lateral transport losses by holes increase with lower base-doping density. BJBC cells with cell thicknesses of about 45µm allow a reduced material consumption combined with a high conversion efficiency of about 21%, assuming a base lifetime of 3000µs, which is only reduced by about 1% absolute if the base lifetime is reduced to 20µs. BJBC cells with base lifetimes of 3000µs show an efficiency of more than 23% for cell thicknesses greater than 290µm; this is only reduced by 0.6% absolute if the cell thickness is reduced from 290µm to 90µm.

Acknowledgements

The authors express their gratitude to J. Hensen for the electrochemical etching, J. Käsewieter for assistance at the lift-off stages, T. Neubert for support in the laser processes, A. Merkle for valuable advice during the processes, and the Renewable Energy Corporation ASA for funding this work.

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Ion implantation for silicon solar cells

Henry Hieslmair, **Ian Latchford**, **Lisa Mandrell**, **Moon Chun** & **Babak Adibi**, Intevac, Santa Clara, California, USA

Cell Processing

ABSTRACT

This paper presents the background and technology development of the use of ion implantation technology in today's crystalline silicon solar cell manufacturing lines. The recent history of ion implantation development and commercialization is summarized, and an explanation is given for the cell efficiency improvements realized using the technique on p-type mono-crystalline cells. The potential economic impact on the factory is also discussed.

Introduction

There are continuing pressures on PV manufacturers to lower manufacturing costs further while increasing efficiency. The efficiency of the module impacts all downstream area-related costs in the installed PV system, such as wiring and bracing structures. Manufacturers have already brought costs down to very low levels through better yield and economies of scale, and are now evaluating various approaches to improving cell efficiency. While standard screen-printed p-type cell efficiency can still be improved, most roadmaps will transition to advanced cell designs to meet the increased efficiency requirements. Thus, any investment in near-term manufacturing solutions has to also offer extendibility paths towards advanced cells and materials. There are numerous high-efficiency device architectures and various technology roadmaps regarding material type, cell architecture, process flow and process equipment. Cell efficiencies are generally predicted to improve as shown in Fig. 1, with the implication that new designs and processes will be adopted by industry to achieve the higher efficiencies.

> "Ion implantation has a unique characteristic in that it is both beneficial to current cell designs and extendible to future cell architectures."

Ion implantation has a unique characteristic in that it is both beneficial to current cell designs and extendible to future cell architectures. In the near term, ion implantation provides higher cell efficiency for P emitters, narrower efficiency distribution and a lower overall cost. Equally important, the manufacturing of many advanced device designs can be significantly simplified by ion implantation. Recent efforts to commercialize high-productivity ion implanters have placed ion implantation technology centre stage in the silicon PV roadmap.

Synopsis of implantation used in solar cells

Throughout the history of implanted solar cells, various implanter tool designs have been utilized, the two main ones being *mass-analyzed* and *non-mass-analyzed*. Mass analysis is performed with a large magnet which bends the ion beam through an aperture. Only species with the proper mass and energy pass through the aperture. The filtered ion beam current is typically significantly less than the initial ion beam current. Non-mass-analyzed implanters, however, feature higher beam currents and lower capital costs, although they exhibit a broad range of ion energies and may co-implant other precursor species such as H+ and F+. Ion sources have also changed over the decades and include glow discharge, microwave and inductively coupled RF plasmas. One of the earliest references to using ion implantation for solar cells was in 1964 by King and Burrill [2], who used a Van de Graaff electrostatic accelerator to accelerate boron or phosphorus ions generated by a microwave ion source.

Glow discharge plasma source designs were common in the 1970s and 1980s [3–6]. A variety of dopant gases – including BF_3, B_2H_6, PH_3 and PF_5 – were utilized as the precursors. One of the most advanced and ambitious implementations of implantation for solar cells was that of the Hoxan Corporation in Japan in 1982 [7]. Using 4" round wafers, Hoxan built an integrated, in-line, computer-controlled, 9MW manufacturing line with a non-mass-analyzed implanter using BF_3 (40keV) to form the rear boron back-surface field (B-BSF), and a second non-mass-analyzed implanter utilizing vapours from a heated solid P source (25keV) to form the emitter. Annealing was performed with a halogen lamp and followed by TiO_2 ARC and screen printing/firing stages. The entire automated manufacturing line also included tabbing and stringing and then module assembly and lamination. Each process was synchronized to five seconds per wafer for a throughput of 720 wafers per hour (wph).

Also in the 1980s, several researchers utilized commercial mass-analyzed beamline implanters for solar cells. Mass-analyzed ion implantation was becoming more important for integrated-circuit applications, in which the energy precision was crucial. Spitzer et al. [8–10] investigated various implantation conditions and anneals for both phosphorus and boron emitters using mass-analyzed implantation; for phosphorus emitters, 18% efficiencies were obtained.

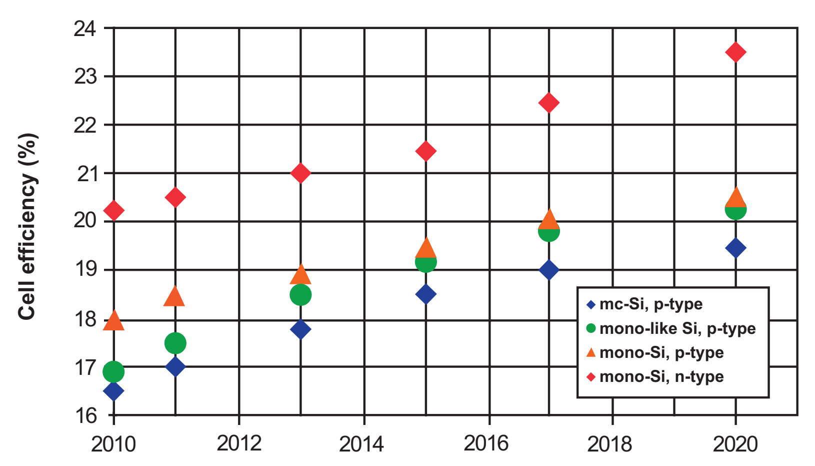

Figure 1. ITRPV Roadmap, March 2012 update: stabilized cell efficiency trend curves [1].

Later, in 1987, using a glow discharge source, Wood et al. [11] demonstrated 19.5% efficiency (AM1.5) using a non-mass-analyzed B_2H_6 (5% in H_2) implant for the emitter (n-type wafer), and non-mass-analyzed PH_3 (1% in H_2) implant for the phosphorus back-surface field (P-BSF). Using oxide passivation and photolithography to pattern evaporated metal contacts, a V_{oc} greater than 660mV was demonstrated. The high V_{oc} obtained demonstrates the exceptional quality of the implanted emitter and BSF, and indicates that the co-implanted hydrogen was not deleterious, despite the dilution of the dopant gas in H_2.

More recently, numerous groups have shown high cell efficiencies on industrial phosphorus emitter cells using modern commercial mass-analyzed implanters. For example, Suniva Inc. has demonstrated high cell efficiencies of ~19% on an industrial scale using a mass-analyzed ion implanter [12,13]. Non-mass-analyzed implanters have also been targeting solar cell applications. For instance, Intevac has demonstrated a continuous flux non-mass-analyzed implant tool – ENERG*i*™ – specifically designed for the solar industry, featuring a 2400wph throughput, sheet resistance uniformities of 1% (σ/mean) wafer to wafer, and a cost of ownership (COO) that is competitive with the standard $POCl_3$ diffusion process. In collaboration with China Sunergy, Intevac has achieved high efficiencies of 19% in an industrial line [14] using the ENERG*i* implanter.

Advantages of ion implantation

Ion implantation in general provides numerous process advantages. Specifically, the advantages of implantation include:

- High-precision dopant doses and profiles
- High uniformity and repeatability
- Single-sided doping capability
- Boron-doping capability
- Patterned doping

For today's standard screen-printed p-type cells, ion implantation yields improved efficiencies through precision phosphorus profiles and high uniformity. The single-sided doping capability simplifies the process flow by eliminating the need for phosphosilicate glass (PSG) removal and edge isolation. Additionally, in situ thin passivating oxides can be easily incorporated during the subsequent anneal. Single-sided ion implantation can benefit thinner wafers by substituting a high-stress alloyed Al-BSF with B-BSF.

Tools and technologies adopted for today's processes must also be extendible and compatible with the future cell designs throughout a manufacturer's development roadmap. With the advent of industrial processes to passivate p-type surfaces, there is increasing benefit in transitioning away from standard cell structures with an aluminium-alloyed BSF. The single-sided doping capability of implantation facilitates this transition by eliminating multiple diffusion-barrier formation and removal steps otherwise required by furnace diffusions to form a B-BSF or P-BSF.

Patterned doping for selective emitters can be accomplished through inserting a shadow mask into the ion beam [15,16]. The ENERG*i* ion implantation can also pattern dopants for selective emitters by using shadow masks so that both the blanket and SE dopants are implanted in the same single-wafer pass through the ion beam.

Because boron diffusion has been difficult to implement cost-effectively in industry, implanting both phosphorus and boron, followed by a single co-anneal, greatly simplifies many designs, such as passivated rear cell designs [13,17,18] and n-type cells with boron emitters [19–22]. For very high efficiencies, ion implantation holds the promise of significant process simplification for interdigitated back-contact (IBC) cells [23–25]. Patterned, single-sided P and B doping with a co-anneal has the potential to make IBC manufacturing far simpler than using repeated diffusion masks and furnace diffusions, as shown in Fig. 2. This comparison of a furnace-based IBC process flow and an implant-based process

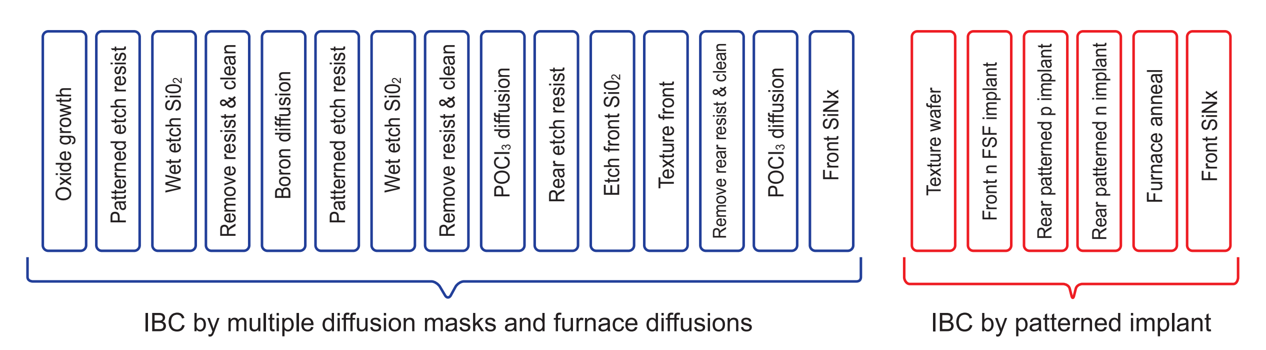

Figure 2. Comparison of process flows for IBC cells by diffusion and by patterned implantation.

flow illustrates the potential process simplification using implantation.

Defect engineering synopsis

Ion implantation damage and recrystallization has been studied for decades. Consequently, very sophisticated models of damage formation and annealing exist, which are beyond the scope of this paper, but a brief synopsis of relevant damage and annealing processes will be given. For phosphorus implantation, the strategy is to form an amorphized surface layer which recrystallizes epitaxially with very few defects during a subsequent higher temperature annealing step. This process is called solid-phase epitaxial regrowth (SPER). The key to minimizing defects through the SPER process is to form a fully amorphized layer with a smooth α/c interface and a minimum of damage beyond the α/c interface. While phosphorus implantation does amorphize the silicon well, boron implantation is more complicated because it does not typically amorphize the top layer of silicon for the doses desired for solar cells.

Except for the lightest elements such as H, as the impinging ion enters the silicon, it transfers most of its energy to the target lattice through collisions. These collisions create local heat and, if more than 15–20eV is transferred to the lattice silicon atoms, one or more Frenkel pairs (Si vacancy + Si interstitial) are created [26]. The damage along the path of the impinging ion, i.e. the collision cascade, is highest near the end of the range where the ion's velocity is sufficiently slow so that nearly every atomic interaction results in a displacement event. Some of the created defects have a very short lifetime, and, with the localized heating assisting the defect mobility, the defects can begin to annihilate (i.e. anneal) on a nanosecond timescale. This dynamic annealing is undesirable because, as mentioned earlier, a well-formed amorphous layer requires significant damage accumulation. Partially amorphized layers or regions with sub-amorphous damage do not typically result in low defects, even after higher temperature annealing. Dynamic annealing can be prevented by cooling the sample to cryogenic temperatures. Implantation studies at such low temperatures illustrate the strong effects of dynamic annealing at higher temperatures. For example, the minimum dose required to amorphize at –150°C is less than 1×10^{15} B/cm^2. In contrast, at room temperature the required implantation dose is ~2×10^{16} B/cm^2 for amorphization.

Other factors contributing to better amorphization include ion species, continuous flux and dose rate [27]. Heavier ions, such as phosphorus, create more damage per ion and therefore require lower doses for full amorphization. Viewing the amorphization process as a dynamic competition between damage accumulation and dynamic annealing, one can understand that a higher dose rate [28] and continuous implant will accumulate damage faster and help form fully amorphized layers. Numerous ion implantation tools raster or pulse the ion beam, thus allowing time between the beam sweeps for dynamic annealing to occur. On the other hand, continuous fluxes and higher dose rates are expected to result in deeper amorphous layers, with less sub-amorphous damage beyond the α/c interface.

During a subsequent annealing step, the amorphous layers will recrystallize epitaxially, with the α/c interface moving towards the surface at a few hundred nm/s at 700°C [29]. Typically, the recrystallization is fully complete by the time the wafer boat is loaded into a furnace at 700°C. Dopants within this regrown epitaxial layer have high levels of activation, even if the dopant concentration somewhat exceeds the solubility during the SPER [30]. However, during the anneal (typically >800°C), equilibrium concentrations will be restored and supersaturated dopants will precipitate or cluster [31]. Thus proper implant and anneal optimization is important for obtaining emitters of the highest efficiency. Additionally, during the anneal the minor sub-amorphization damage, which lies deeper than the initial α/c interface, can be minimized or completely annealed as the phosphorus diffuses deeper into the silicon.

The ENERG*i* implantation tool was designed with both the needs of the solar market and defect-free emitters in mind. The ENERG*i* tool cools the wafer, which undergoes a single pass through a continuous and high-flux phosphorus ion beam. The difference between a rastered and a continuous flux implantation is schematically illustrated in Fig. 3 for the same total dose (area of each coloured region). At any given point on a silicon wafer, the rastered ion beam allows periods of time for dynamic annealing to occur and may result in poorer amorphized layers.

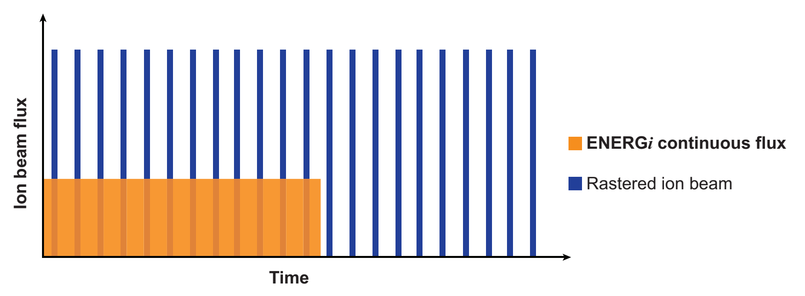

Figure 3. The ion beam flux observed for any given point on a wafer for a rastered ion beam and for a continuous flux ENERG*i* ion beam for the same dose (area of each coloured region).

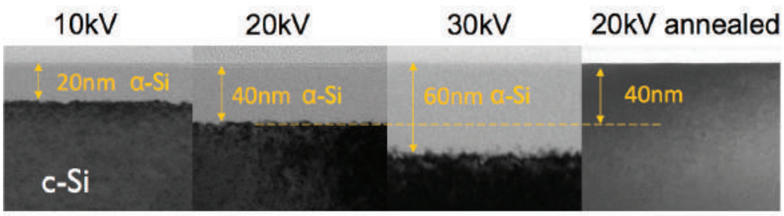

Figure 4. Transmission electron microscope (TEM) images of ENERG*i* implanted samples, showing amorphization at 10kV, 20kV and 30kV. Also shown is the defect-free recrystallization of the 20kV implanted sample.

At Intevac, fully amorphized layers with doses as low as 1×10^{15} P/cm^2 have been demonstrated. Examples of amorphization at different energies using the ENERG*i* continuous-flux implantation tool are shown in Fig. 4, as well as the defect-free recrystallization of the 20kV implanted sample.

Boron does not amorphize silicon at doses of interest for solar cells. Instead of SPER, the sub-amorphous implant damage needs to be annealed at higher temperatures. Good emitters have been demonstrated by annealing at high temperatures such as 1000°C. Some problems with V_{oc} or internal quantum efficiency (IQE) response have been reported for B+ implanted emitters despite low J_{0E} values having been achieved [32–34]. However, other studies have shown excellent results with similar B+ implanted emitters [21,22]. To be successful, boron implantation for solar cells will depend on the right tool, implant and anneal.

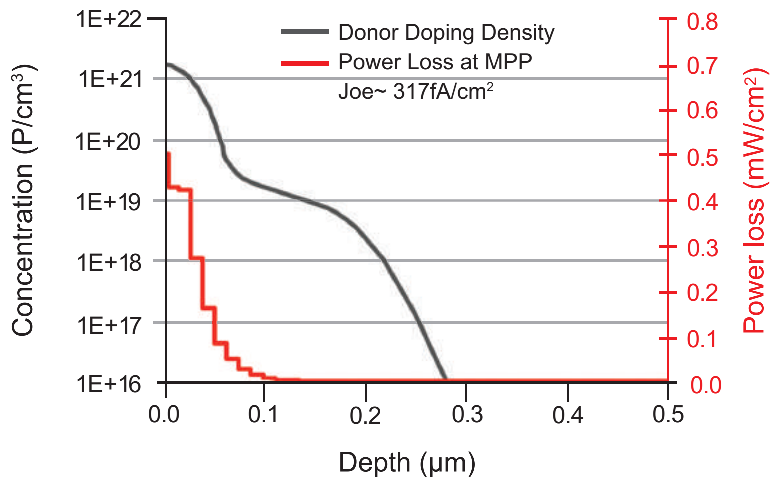

Figure 5. PC1D simulation illustrating typical power losses due to high phosphorus concentrations in the near-surface region (<50nm).

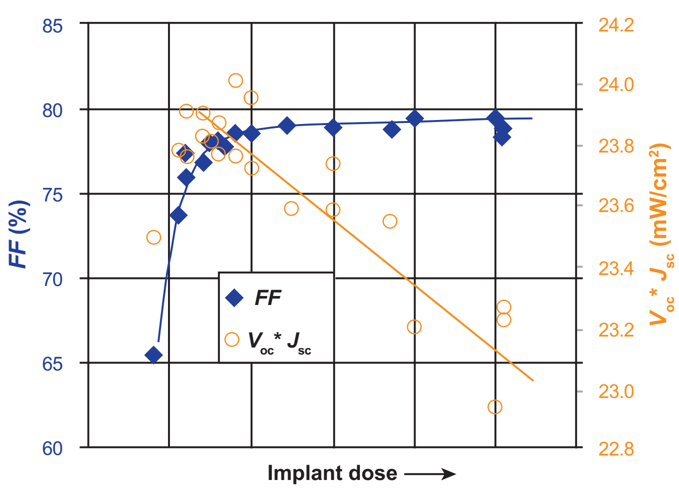

Figure 6. The effect of implanted phosphorus dose on *FF*, V_{oc} and J_{sc}. At lower phosphorus implant doses, V_{oc} and J_{sc} improve, whereas *FF* degrades abruptly.

Efficiency improvements for standard P emitters by ion implantation

The efficiency gain from ion implantation in today's phosphorus emitters is based on precisely controlling the near-surface phosphorus dose. Any phosphorus emitter optimization entails maximizing the sheet resistance while minimizing carrier recombination and contact resistance to the front metallization. While the sheet resistance is a function of the entire profile shape, the recombination and the contact resistance are very sensitive to the portions of the emitter containing the highest concentration of phosphorus, i.e. the first ~50nm of the emitter. Fig. 5 shows a PC1D simulation, illustrating the general importance of the near-surface region. The black curve indicates the phosphorus profile, with concentration values on the left axis; the red curve is an approximation of the power loss (as a function of depth) caused by carrier recombination. (Fig. 5 is intended only to illustrate the importance of the near-surface region – various assumptions and simplifications were made that are outside the scope of this paper.)

By lowering the near-surface phosphorus dose, improved emitters and higher efficiency cells can be fabricated. An improvement in V_{oc} and J_{sc} with decreasing dose is shown in the data plotted in Fig. 6: as the total phosphorus dose is decreased, recombination in the emitter is reduced, which results in improved V_{oc} and J_{sc}.

However, below a threshold phosphorus dose the contact resistance to the front metallization may increase significantly. The industrial Ag-based screen-printed metallization requires high (degenerate) doping levels at the Ag-Si interface in order to make low-resistance tunnelling junctions [35]. This effect places a lower limit on the reduction of the near-surface phosphorus dose. In Fig. 6, the fill factor (*FF*) is also plotted as a function of implanted phosphorus dose. For a fixed anneal, the near-surface dose will be proportional to the total implanted dose. Below a threshold dose, the paste and firing conditions result in higher contact resistance and degraded *FF*. While new pastes are able to contact lower surface concentrations, a strong drop in *FF* will still occur if the concentration is too low. Thus, for industrial high-efficiency emitters the near-surface phosphorus dose

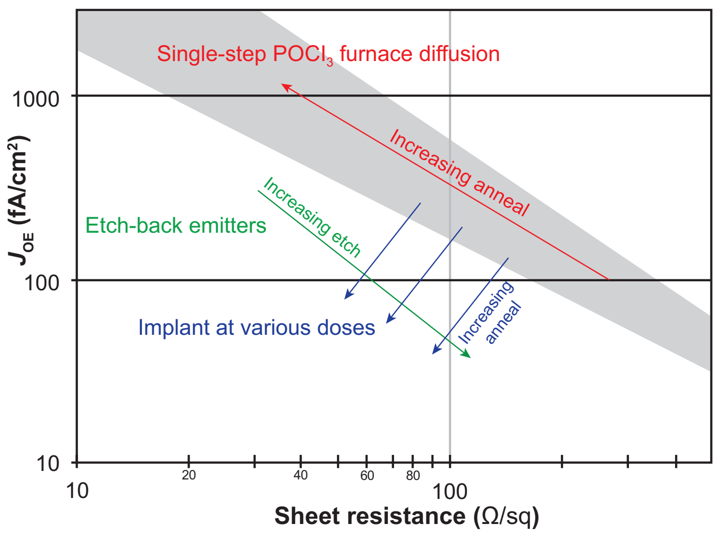

Figure 7. Process trajectories for various emitter formation techniques.

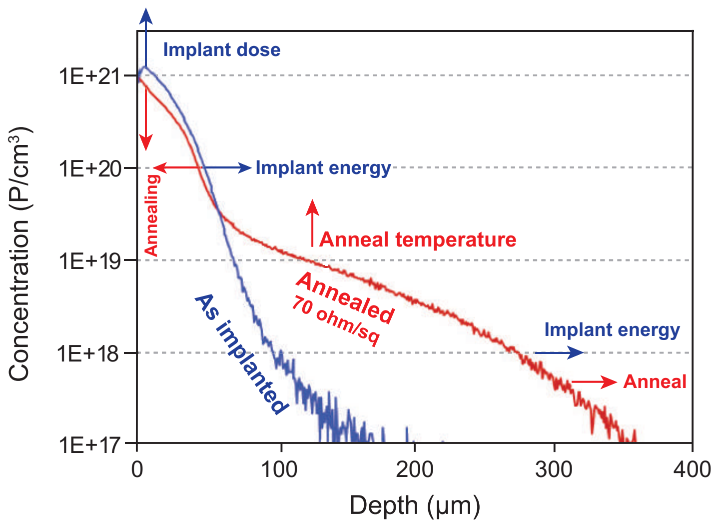

Figure 8. Impacts of various implant and anneal parameters for tailoring P profiles.

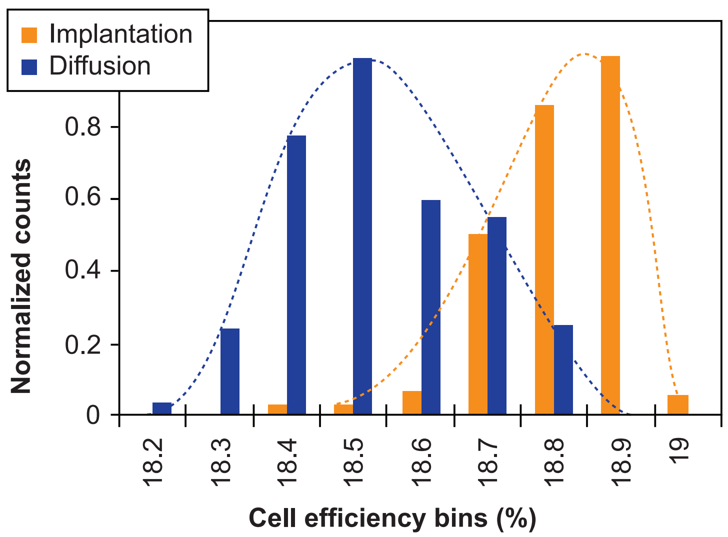

Figure 9. Comparison of industrial cells made by $POCl_3$ diffusion and ion implantation.

must be precisely optimized and controlled across the wafer and from wafer to wafer.

Such near-surface phosphorus dose control is more difficult with $POCl_3$ diffusion. In this case the phosphorus dose *and* phosphorus drive-in are increasing during the anneal. The near-surface dose is very sensitive to temperature and ambient gas variations in the furnace. This process trajectory (increase in dose and J_{0E} with reduction in sheet resistance) is illustrated in Fig. 7 by the red arrow. More complex furnace recipes involving multiple anneal plateaus and ambient gases [9] can, to a limited extent, alter the near-surface phosphorus concentration and improve J_{0E}. The $POCl_3$ process is therefore depicted as a wider range by the grey area in Fig. 7; for illustration purposes, the emitter etch-back [36] process trajectory is also included and is indicated by the green arrow. During the etch-back, the surface and peak concentrations are reduced, resulting in a lower J_{0E} emitter and higher sheet resistance.

In contrast, the ion implantation process separates the dose step and the drive-in step in order to precisely control and tailor the final phosphorus profile. During the anneal, the as-implanted phosphorus dopant starts to diffuse into the silicon. This redistribution of the implanted P results in a reduction in both J_{0E} and sheet resistance as indicated by the blue lines in Fig. 7, where each blue line represents a different phosphorus dose. This process trajectory is somewhat orthogonal to the typical $POCl_3$ diffusion.

An additional process advantage of ion-implanted phosphorus emitters is that an in situ passivating oxide can be rapidly grown during the anneal. Bhosle et al. [37] have shown a +0.35% absolute efficiency gain by utilizing an in situ oxide. The high surface concentrations of phosphorus accelerate oxide growth and allow for thicker oxides in short periods of time [38].

The final profile of the cell can be finely tailored by a combination of implant dose and energy, as well as anneal time, temperature and ambient. Fig. 8 summarizes the main parameters of the implant and anneal which control the various portions of the final P profile. Notice that, even after the anneal, the near-surface dose is largely controlled by the initial implant dose and energy. As discussed earlier, it is vital to optimize and control this near-surface P to achieve the best balance of contact resistance to the surface metallization and the highest V_{oc} and J_{sc}.

Performing such an optimization in an industrial line results in a higher efficiency than typical $POCl_3$ diffusion is capable of. This has been demonstrated by Rohatgi et al. [13], who showed an increase in absolute efficiency of +0.3% to +0.8%, and by Wang et al. [39], who showed an improvement in absolute efficiency of more than 0.4%

over $POCl_3$. In cooperation with China Sunergy, Intevac, using their ENERG*i* ion implantation tool, compared implanted cells with standard $POCl_3$ cells processed on a China Sunergy industrial process line [14]. The normalized histogram shown in Fig. 9 already shows a clear improvement using ion implantation with only preliminary optimization. Intevac recently fabricated cells on an industrial manufacturing line with another partner and demonstrated average cell efficiencies exceeding 19.1% (n>2000 wafers). This result also represented a significant improvement over the cell efficiencies for standard $POCl_3$ diffusion. The basic process steps are shown in Fig. 10.

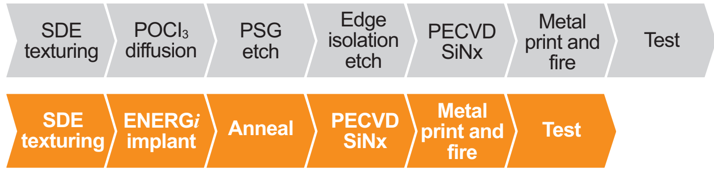

Figure 10. Process simplification and cost reduction by eliminating PSG etch and edge isolation.

Economics

The COO of the recent commercial high-throughput ion implanters is compelling because not only are higher cell efficiencies obtained, but also the distribution of the cell efficiency is narrower. Owing to its high throughput, the ENERG*i* ion implantation tool is cost competitive with the standard $POCl_3$ process via the higher final cell efficiencies and the cost reduction by the elimination of PSG etch and edge isolation.

After process optimization, the ENERG*i* phosphorus implant operating at 2400wph can conservatively improve the cell efficiency by more than 0.5% absolute over the diffusion process. The impact of this on the output of a manufacturing line is an increase of more than 2MWp/year with a value of $1.4 million/year. Narrowing the distribution in cell efficiencies can increase the value even more by virtue of a reduction in scrap, and higher module prices at the higher efficiencies. The investment in the line is also minimized by the fact that adding ion implantation removes the need for wet-etching steps (phosphorus glass etch and edge isolation). This elimination removes approximately $1 million of capital cost from the line and also removes the acid and water running costs (~$0.3 million/year). With these considerations, the payback time of an ion implantation system running at 2400wph is approximately 1.3 years. This is one of the most efficient payback schedules possible in the solar manufacturing business today. The payback time is even shorter for boron implant with higher cell efficiency improvements. As this value is realized, ion implantation systems will become ubiquitous and highly valued by today's Tier 1 solar cell and module manufacturers. Lastly, the Intevac ENERG*i* tool has a very small footprint compared with other tools which handle similar throughput of wafers on the fab line (Fig. 11). This makes retrofitting existing lines for phosphorus implantation easier.

Figure 11. View of the Intevac ENERG*i* ion implantation tool: the actual implantation section is the size of a small minivan.

Conclusion

In the solar cell technology roadmap a transition is taking place in which diffusion processes that have been used for many years are now being replaced by new, cell-efficiency-enhancing ion implantation solutions. Ion implantation offers solar cell manufacturers the capability to extend cell efficiency beyond 19% with a narrower cell efficiency distribution. Additionally, ion implantation offers a path towards the commercialization of new advanced cell architectures, n-type material and IBC cells. A continuous-flux plasma-based ion implantation solution provides the necessary economic solution to achieving this with a very efficient payback schedule.

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Dr. Henry Hieslmair is currently Principal Solar Scientist at Intevac, managing tool design and processes for ENERG*i* ion implantation for solar cells. With 20 years' experience in the silicon solar field, he has researched a wide range of topics from basic defects in silicon materials to developing an entirely laser-doped IBC on thin silicon. Henry holds numerous patents and has published over 40 papers in solar technology.

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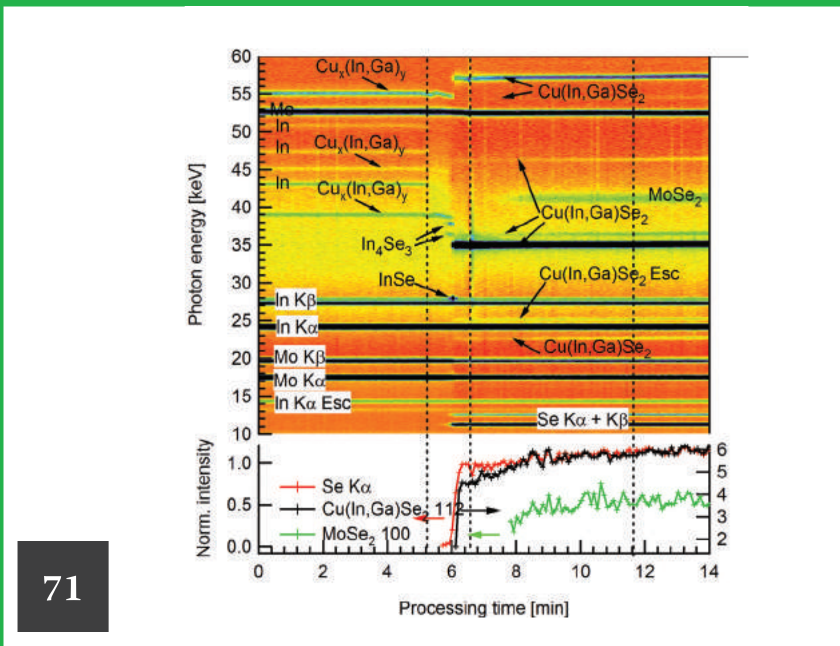
Thin Film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$MoSe_2$
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Belectric acquires Konarka Technologies

Belectric has advised that the deal to acquire Konarka Technologies has been completed, with an agreement reached between the two companies.

Konarka Technologies applied for insolvency earlier this year and began negotiations with several investors and will now operate as Belectric OPV. The company will continue research, development and production, as well as international distribution of its printed PV cells.

Over the coming year, Belectric OPV will look to increase the service life of the organic solar cells, performing different tests over the first phase.

Source: Konarka Technologies

Belectric has advised that the deal to acquire Konarka Technologies has been completed.

R & D News Focus

XsunX prepares for trials of new CIGS system

California-based XsunX has completed the assembly of its new 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.

Tom Djokovich, CEO of XsunX, said: "Many of the potential customers are interested in the smaller footprint and cost-competiveness of our scalable system to service regional demand and employment goals."

Lux Research: Manufacturers need to innovate to survive solar shakeouts

Solar panel manufacturers need to acquire innovative production equipment in order to cut costs, increase margins, and offer differentiated products, a report issued by Lux Research's Solar Components Intelligence service has warned.

The report found that current wafer techniques could be improved to reduce wastage. CIGS thin-film PV and new cell designs require standardization to drive higher efficiencies, performance and yield – lowering capex and helping manufacturers attain scale and competitive production costs.

Business News Focus

Robert Roche takes on VP of sales role at Ascent Solar

Robert Roche has been selected as the new vice president of sales, marketing and communication for Colorado's flexible CIGS solar panel developer, Ascent Solar Technologies.

A 25-year veteran of the sales and marketing industry, Roche joins Ascent Solar after working for two years as VP of sales and business development at United Solar.

First Solar honours suppliers with NOVA award

US-based thin-film module manufacturer First Solar has recognised five premier suppliers with its NOVA award at its second annual Supplier Recognition Day for their work in 2012.

First Solar said that its work with Morgan Crucible improved its critical materials processing while NSG helped it achieve an efficiency roadmap while dually reducing costs. Expeditors International was credited with assisting First Solar enter new markets and keep in compliance with local laws and regulations. Oryx was lauded for promoting cost reductions at First Solar through R&D efforts and Rapid Manufacturing was congratulated for providing flexibility on project support and showing its commitment to First Solar initiatives.

Singulus Technologies to reduce workforce on weak demand

Cost cutting measures and inventory write-downs at PV equipment supplier, Singulus Technologies, will amount to €43.3 million as the company reported preliminary third quarter 2012 financial results.

A lack of equipment orders at its subsidiary, Singulus Stangl Solar, which focuses on wet chemical processing tools and technology, will lead to a workforce reduction of approximately 40% at its facility in Fürstenfeldbruck, Germany. The workforce reduction will be implemented by the end of the year, according to the company.

Singulus said it was projecting full-year losses of between €54-56 million.

Bankrupt Abound officials face fraud investigation

Officials from Colorado-based Abound Solar are facing a criminal investigation over possible fraud, it has emerged.

The District Attorney's Office for Weld County, Colorado, has revealed it is investigating an unspecified number of employees of the PV manufacturer, which declared bankruptcy in July and is no longer operating.

Source: First Solar

First Solar held its first annual NOVA award ceremony in 2011.

Source: Images_of_Money

Abound: officials face criminal investigation.

The DA's office said its probe was investigating three main allegations.

The first is that Abound officials knew they were selling defective products but persuaded investors to invest in the company anyway.

The second main allegation centres on whether Abound misled financial institutions when it applied for a bridging loan to keep the company afloat until it received federally guaranteed loans. The company received a US$400 million loan from the US Department of Energy, US$70 million of which it had drawn down before going bankrupt.

A third allegation concerns possible consumer fraud, and whether Abound officials knowingly sold consumers defective products.

The office of DA Ken Buck said no charges had been made in connection with the investigation.

SunShot offers US$2.6 million towards solar technology research

Research laboratory SLAC has been awarded over US$2.6 million from the US Department of Energy to undertake three research projects into cheaper materials and manufacturing techniques for solar panels.

The organisation is one of 10 DOE Office of Science laboratories operated by Stanford University.

The first project will look at a low-cost printing technique using solar panel materials as ink could be the solution to lowering the cost and possibly improving the performance of flexible panels. This project has received US$878,578.

Source: SLAC

SLAC has been awarded over US$2.6 million for three years work.

The second project, in receipt of US$896,250, will study how electrons travel throughout the layers in a solar panel in order to develop new top-layer materials that let light through more efficiently.

The greatest amount of money, US$899,000, is going to the study of heat treatment on solar panel components. Samples will be rapidly heated to about 500 to 1,000 degrees Celsius, with data collected in hundredths-of-a-second intervals.

MOFCOM approves sale of Oerlikon's solar division

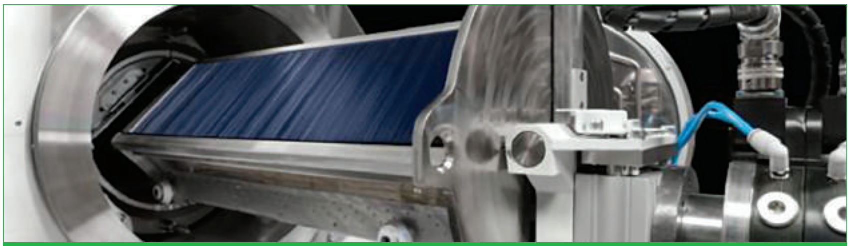
The sale of Oerlikon Group's loss-making Oerlikon Solar to Tokyo Electron (TEL) has received regulatory approval from the Chinese Ministry of Commerce.

The sale to Japanese semi-conductor equipment supplier TEL was originally announced on March 2 and according to reports, TEL is paying a purchase price of US$275 million for the thin-film firm.

With the Chinese approval, all necessary regulatory requirements to close the deal have been fulfilled. As a result, the companies are now entering the closing process.

Beneq plans Russian subsidiary

Beneq, a Finland-based provider of equipment for advanced thin-film coatings, has announced plans to establish a subsidiary in Russia and



Source: Beneq

Beneq has announced plans to establish a Russian subsidiary and open an application development and service laboratory called AppLab.

set up operations in the Commonwealth of Independent States.

The move is in line with the company's strategy to expand into existing and emerging markets. Its strategy has received support from the state-owned Rusano Corporation, which made a €25 million investment in the company earlier this year in April.

In addition to the planned subsidiary, Beneq has also announced plans to open an application development and service laboratory called AppLab in order to promote and implement cutting-edge thin-film technologies and create globally competitive products and industrial solutions for Russia and global markets.

DuPont experiences 48% income drop in Q3 2012

DuPont's third quarter results show a 48% decrease in income from continuing operations, down US$277 million from US$579 million in Q3 2011 to US$302 million.

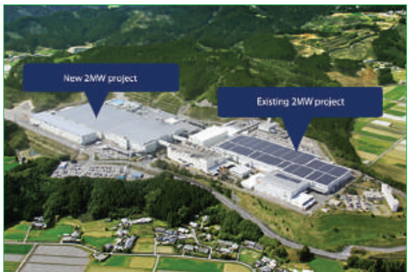
A restructuring plan has been implemented, expected to deliver pre-tax cost savings of about US$450 million (US$300 million in 2013). The plan includes the dismissal of 1,500 employees globally in the next 12-18 months.

Sales of US$607 million were down 28%, primarily due to soft photovoltaic volume and lower silver cost pass-throughs.

Thin-Film Order Focus

Showa Shell and Solar Frontier plan 2MW expansion atop Kunitomi thin-film plant

Showa Shell Sekiyu has announced plans to develop a 2MW PV plant on the rooftop of Solar Frontier's Kunitomi manufacturing facility in southern Japan.



Source: Solar Frontier

Showa Shell Sekiyu will build an additional 2MW PV plant atop Solar Frontier's thin-film module manufacturing facility in Kunitomi, Japan.

The new 2MW PV plant will be built atop one of the facility's other buildings. It will also use Solar Frontier's CIS thin-film solar modules and is scheduled to complete by the end of 2012. Solar Frontier will lease the rooftop to Showa Shell Sekiyu.

The new 2MW project represents Showa Shell Sekiyu's second commercial solar power plant following its Niigata Yukigunigata Megasolar power plant in Niigata Prefecture, Japan. When complete, electricity generated from the array will be sold to Kyushu Electric Power Company.

Solar Frontier's Kunitomi facility began producing CIS thin-film solar modules in February 2011 and has an annual production capacity of 900MW making it, the company claims, the world's largest CIS thin-film solar module production facility.

Source: DuPont

DuPont's third-quarter results show a 48% decrease in income from continuing operations.

Voltech Group and NanoPV plan manufacturing plant and solar park

NanoPV and the Voltech Group are to build a 100MW solar module manufacturing plant and a 100MW solar farm in India.

According to *The Hindu*, the plant will be set up in a factory building near Chennai, India, which at one time produced textiles. NanoPV will supply plant machinery and set up a production line at the site. Initial plant capacity will be 10MW, and eventually be extended to 100MW.

The two companies have already begun construction of their second project, a 100MW solar farm near Tuticorin.

NanoPV and the Voltech Group noted that they intend to enter power purchase agreements with industrial consumers in the state to form a "group-captive" structure. Both the manufacturing facility and solar farm hold a US$18.5 million price tag.

Ascent Solar selected for US$750,000 award by Air Force SBIR program

Ascent Solar Technologies has been chosen for an Air Force Small Business Innovative Research (SBIR) Phase 2 grant valued at US$750,000.

The SBIR Phase 2 award will be used by Colorado-based Ascent Solar Technologies to establish a next-generation PV product using its flexible monolithically integrated cooper-indium-gallium-diselenide (CIGS) technology.

The award is still subject to contract finalisation, but is anticipated to run for 24 months.

First Solar back to full-capacity utilisation in Q4

Despite lower Q3 2012 revenue of US$839 million, down from US$957 million in the last quarter, First Solar said that CdTe thin-film module production increased 33% from Q2 levels reaching 490MW.

A strong project pipeline meant that the company would see production capacity utilization rates reach between 90 and 95%, effectively full capacity in Q4. First Solar had utilization rates of 63% in Q2 and reached 83% in Q3.

However, the company reiterated that its Frankfurt Oder manufacturing facility in Germany would continue production until the end of this year when production would be permanently shut down.

Topaz marks milestone with millionth PV unit

MidAmerican Solar and First Solar, developers of the 550MW Topaz solar farm in California, have installed the project's millionth PV unit.

This marks a significant milestone in the development of Topaz, which will eventually feature up to nine million individual modules.

Construction work began on site late 2011, with the first module installed in May this year. The project is due for completion in 2015, after which Pacific Gas and Electric Company will buy the electricity generated by the plant on a 25-year power purchase agreement.

Saint-Gobain helps develop Solar Energy in Saudi Arabia

Saint-Gobain has signed a Memorandum of Understanding with HRH Prince Faisal Bin Salman Bin Abdulaziz Al Saud, to set up a high-tech company in the solar energy sector in Saudi Arabia.

Under the terms of the Memorandum, Saint-Gobain will provide technical assistance and engineering expertise to build and operate a CIGS (Copper, Indium, Gallium, Selenide) thin film PV module manufacturing facility in Saudi. The project is part of a larger program which includes the construction of solar power plants in the Kingdom.

Source: Saint-Gobain

Saint-Gobain has signed a MoU to set up a high-tech company in Saudi Arabia.

Solliance initiative starts Solar Flare project to make thin-film competitive

A who's who of select research institutions in the Eindhoven-Leuven region of Belgium have teamed-up to boost the competitiveness of CIGS thin-film technology with conventional crystalline silicon technology that would ultimately support the overall cost reduction of solar energy. Working under the Solliance initiative, the Solar Flare project includes ECN, TNO, imec, Holst Centre, TU/e and the University of Hasselt/IMO, which will also aim to make thin-film PV a viable alternative to Si PV technologies.

The Solar Flare project members said that thin-film module efficiencies would need to be boosted to around 17% to be competitive with c-Si modules of around 17% seen on the market currently. The members will also develop and implement a specific Cost of Ownership model for TF-PV to provide the data required for commercial production purposes.

Product Reviews

Singulus Technologies

CISARIS furnace from Singulus provides optimized CIGS absorber formation

Product Outline: The CISARIS oven from Singulus Technologies is an in-line rapid thermal processing tool, designed for CIGSSe absorber formation on large area glass substrates. The main features of the CISARIS include a high uptime and mechanical yield, as well as a fast cycle time, which, in combination with the robust selenization process, lead to a production capacity of over 25 MWp per year.

Problem: Correct CIGS absorber formation is dependent on the control in the composition of the deposited films in a reliable and repeatable manner for high-volume production applications.

Solution: CISARIS is based on a previous generation of proven selenization ovens. CISARIS can safely handle the thermal processing of large glass substrates of over 1 square metre at temperatures up to 600 degrees Celsius under a toxic and corrosive gas atmosphere. High heating and cooling rates, combined with improved temperature homogeneity during all process stages, are the key factors which allow the formation of an optimal CIGSSe absorber, required for the production of high-efficiency solar modules.

Applications: In-line rapid thermal processing equipment, designed for the CIGSSe absorber formation.

Platform: CISARIS is a second generation in-line selenization furnace with optimized cycle time. It provides rapid heating (up to 4°C/s) of large substrates with metal precursor coating (CIG) with uniform heating up to 550°C by using optimized IR radiators for achieving the required crystal quality. Uniform cooling of the substrate to avoid glass warpage is enabled by improved temperature control (mean variation < 5 °C) at all process stages.

Availability: Currently available.

Manz AG

Manz new ISS 1200 provides compact in-line sputtering for CIGS thin-film modules

Product Outline: Manz AG has complemented its range of products for the thin-film solar market with a vacuum system for vertically coating substrates. The new coating system ISS 1200 is a compact and modular in-line sputter system (ISS) that allows manufacturers to get a better rate of raw material utilization.

Problem: To provide high-efficiency CIGS thin-film modules all the relevant steps in the process need to be closely integrated – including laser processes, wet-chemical processes and now also vacuum-coating processes, as well as their fully automated connection and intelligent controls systems. Combined, improved yield and lower costs can be achieved.

Solution: The system operates on the principle of physical vapour deposition, in which raw materials, for example molybdenum, are converted into their gaseous state with the help of a physical process and are subsequently deposited onto the glass substrate as a conductive layer. Sputter systems offer short takt times, require little maintenance and can be easily integrated into both new and existing production lines.

Applications: Modular in-line sputter system for CIGS thin-film materials.

Platform: The new Manz ISS 300 to ISS 1200 product platform was developed by Manz Coating GmbH, founded in 2010 in Karlstein.

Availability: September 2012 onwards.

4JET Technologies

4JET's laser-scribing system for flexible solar cells allows true roll to roll processing

Product Outline: 4JET Technologies have introduced a new laser-scribing system for flexible thin-film solar cells. The unique 4FLEX tool design enables the P1-P3 serial integration of flexible CIGS, a-Si- and organic thin-film solar cells on polymer- or metal substrates, thus allowing new approaches for module design.

Problem: The monolithic integration allows true roll to roll processing and provides for advantages over connecting individual small cell shingles to a module. Handling of flexible substrates requires different handling regimes compared to conventional glass substrates.

Solution: The 4JET design is based on a patent-pending foil-and-beam delivery system that guarantees a precise standoff distance between laser optics and foil. At the same time, the tool allows full area processing of the entire foil surface, with up to 10 parallel laser beams. The monolithic integration allows true roll to roll processing and offers advantages over connecting individual small cell shingles to a module. The machine design is also suitable for processing other flexible materials such as printed electronics and battery foils.

Applications: P1-P3 serial integration of flexible CIGS, a-Si- and organic thin-film solar cells on polymer or metal substrates.

Platform: The 4FLEX system uses specially developed handling techniques for the foil substrate during laser processing that keeps a precise gap between the laser and substrate, necessary for the ablation process control requirements. Laser beam profiles are customized to the required substrate as well as certain throughput requirements.

Availability: Currently available.

Current topics in CIGS solar cell R&D: Overcoming hurdles in mass production

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ABSTRACT

Since the demonstration of the first $CuInSe_2$ solar cell in 1974 by scientists at Bell Laboratories, a lot of effort has been put into the development of cost-effective processes for highly efficient $Cu(In,Ga)(Se,S)_2$ – or CIGS – solar cell devices. In 2012 these efforts led to the first gigawatt CIGS solar module production facility operated by Solar Frontier, a company that has a long history in R&D and originates from ARCO Solar, who developed the first commercial CIGS solar modules at the beginning of the 1990s. However, several start-up companies employing CIGS technology are presently struggling in the currently harsh market environment. Even though world-record laboratory solar cells now demonstrate 20.3% efficiency using a three-stage co-evaporation process, and full-size modules achieve 14.6% employing a similar method, efforts in research and development are more important than ever in order to increase cell efficiency, to bridge the gap between cell and module efficiencies, and to develop cost-effective and robust manufacturing processes. This paper gives an overview of current research topics under investigation by research institutes and industry, with a main focus on CIGS absorber formation. Along with other research results published by groups all over the world, this paper covers recent research results obtained at the Helmholtz-Zentrum Berlin für Materialien und Energie (HZB) and briefly mentions the work of the Photovoltaic Competence Center Berlin (PVcomB), a joint initiative of the Technical University of Berlin (TU Berlin) and HZB.

Introduction and history

After a demonstration of the first $CuInSe_2$ solar cell in 1974 by scientists at Bell Laboratories [1], the first solar cells were made from single-crystal $CuInSe_2$ in 1975 by Shay and co-workers [2]. Since then there have been two main process routes for manufacturing CIGS thin-film solar cells:

1. Co-evaporation of elements – the so-called 'Boeing process,' developed by Boeing engineers [3].
2. Sequential processing of a Cu:Ga/In precursor layer in an atmosphere containing selenium (Se) and/or sulphur (S), based on a process first published by Grindle et al. [4].

Solar cells from both processes having the typical design of a molybdenum (Mo) back contact / absorber layer / CdS buffer layer / zinc oxide (ZnO) window layer were developed by ARCO Solar in 1987 [5], as shown in Fig. 1.

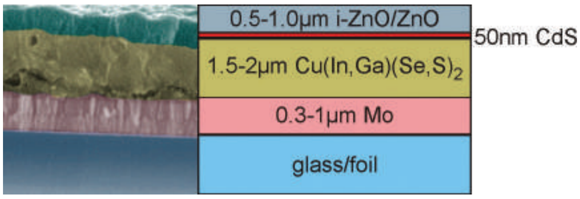

Figure 1. Structure of a typical thin-film CIGS solar cell device developed by ARCO solar [5]: (left) SEM image of a cross-section of a CIGS-based solar cell; (right) schematic overview.

Milestones marking the evolution of thin-film CIGS solar cells are illustrated in Fig. 2 and are as follows:

1. Control of the ratio of Cu to group III elements – best cells for Cu/III < 1 in the case of selenide-containing chalcopyrites to avoid the formation of $CuSe_x$.
2. Preparation of a thin CdS buffer by chemical bath deposition, which leads to a conformal growth of a 50nm-thick CdS layer and eliminates shunting paths.
3. Cu-rich growth regime during CIGS absorber layer formation, which improves morphology and electronic properties.

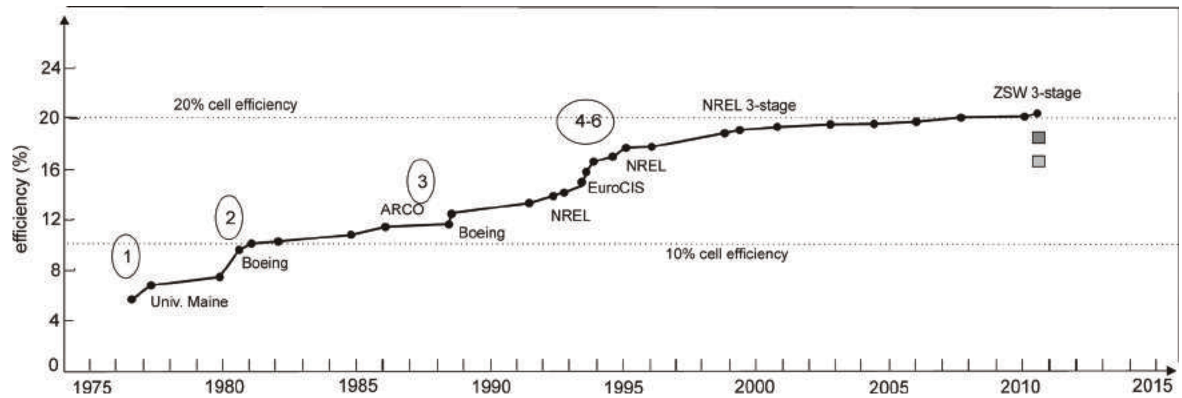

Figure 2. Record efficiency development of CIGS solar cells (after NREL http://www.nrel.gov/ncpv/).

Process	CIGS	Module	Hersteller
PVD	Co-evaporation	Monolithic glass/glass	Würth (D), Solibro (D)
		Flexible cells / flexible modules	Global (US,D), Ascent (US), Solarion (D)
	Reactive sputtering	Flexible cells / glass/glass modules	Miasole (US)
Sequential	Sputtering + RTP	Monolithic glass/glass	Avancis (D), Sulfurcell (D), Heliovolt (US), Stion (US)
	Sputtering + Annealing	Monolithic glass/glass	Solar Frontier (J), Honda Soltec (J), Bosch CISTech (D)
	Electrodepositing + RTP	Flexible cells / flexible modules	Solopower (US), Odersun (D)
	Inkjet printing + RTP	Flexible cells / glass/glass modules	Nanosolar (US), ISET (US)

Table 1. Family tree of CIGS processing routes and related companies.

4. Sodium supply during CIGS absorber layer formation, which further improves morphology and electronic properties.
5. Incorporation of gallium (Ga) into the optimized band gap of the CIGS absorber layer.
6. Incorporation of sulphur (S) into the CIGS absorber layer in the case of increased open-circuit voltage through sequential processing by increasing the band gap of the front part of the absorber layer.

As can be seen in the development chart (Fig. 2), in the past ten years no major improvement has been made in terms of solar cell efficiency. The record efficiency of 20.3% is mainly a result of fine-tuning the deposition parameters and not a fundamental improvement of the device or deposition process. From the theoretical point of view, a single-junction device should have a conversion efficiency of 25% or more. In the last decade R&D has concentrated on two topics:

1. Understanding the device limitations by analyzing the material and device properties.
2. Finding deposition processes and process control tools which are scalable and robust to achieve mass production.

This paper focuses on the hurdles which have to be overcome to achieve successful mass production and how these hurdles are tackled in current R&D activities. In particular, the R&D work performed at HZB and PVcomB will be discussed. PVcomB operates to 30×30cm^2 thin-film solar module R&D baselines to help bridge the gap between fundamental research and industry [6].

CIGS module production processes – what choices are available?

In contrast to a-Si solar module production, there is an abundance of different process routes available and under development by different companies for manufacturing CIGS-based solar cells. Only the back- and front-contact layers are the same for all approaches: Mo is used as the back contact, while a bi-layer made from intrinsic ZnO and doped ZnO serves as the front contact. The formation of the CIGS absorber layer is divided into two different process types:

1. Simultaneous co-evaporation of the elements in a high vacuum (PVD).
2. Sequential processing by performing first the deposition of a precursor layer, followed by a more or less fast annealing step to create the CIGS absorber layer.

In the case of sequential processing, there are several ways to deposit the metal precursor layer: magnetron sputtering, electrodeposition and ink printing of metal nanoparticles in a solution. Whether a selenium layer is added to the precursor depends on the annealing process: fast annealing processes deposit a selenium layer before the annealing, while slow annealing ones provide selenium via H_2Se. Common to all sequential processing routes is an annealing in a H_2S atmosphere after the selenization.

> "Annealing at atmospheric pressure using elemental Se and S appears to avoid the highly toxic H_2Se."

Reactive sputtering of CIGS with H_2Se as the reactive gas is currently under investigation, as it might combine the advantages of the co-evaporation process in terms of stoichiometry control and magnetron sputtering. In particular the activation of Se in the plasma might lead to lower process temperatures. In addition, a process of annealing at atmospheric pressure using elemental Se and S appears to avoid the highly toxic H_2Se.

As well as the deposition process, one has the choice of using rigid or flexible substrates. Mostly standard float glass is used as a substrate since it has several advantages, such as low cost, flatness, shielding properties against environmental impacts, and a source of sodium (Na). Flexible substrates offer the possibility of new lightweight module designs and compact deposition tools, but Na has to be supplied by additional sources. In the case of metal substrates, barrier layers have to be applied in order to avoid metal diffusion into the CIGS absorber layer.

After the CIGS absorber formation, a buffer layer has to be deposited. Historically this layer has been CdS, and the chemical bath deposition (CBD) process works best, but other materials and deposition techniques are available and used for applying the buffer layer. In Japan especially, Cd-free buffer layers have to be used: CBD-Zn(O,OH,S) and CBD-InS are therefore established alternatives to the CdS buffer layer.

Last, but not least, one has to opt for either monolithic interconnection of cells within the deposition process, which is one of the advantages of thin-film solar modules, or making solar cells with contact grids.

Substrate and back contact – not so many options, but Na is necessary

As described earlier, soda-lime glass is the standard substrate for CIGS-based solar modules, its main purpose being to act as a Na source, as Na significantly improves the device performance. The control of the Na supply, however, is very limited and depends not only on the process temperature and duration, but also on the history of the glass. To achieve a better Na control, the application of a barrier layer and deposition of an additional Na source is therefore becoming standard in the industry.

Several different ways of supplying sodium are possible. In the case of co-evaporation, the deposition of a NaF layer onto the Mo back contact is common. In recent years, one manufacturer of targets for magnetron sputtering managed to dope the Mo target with Na, which can

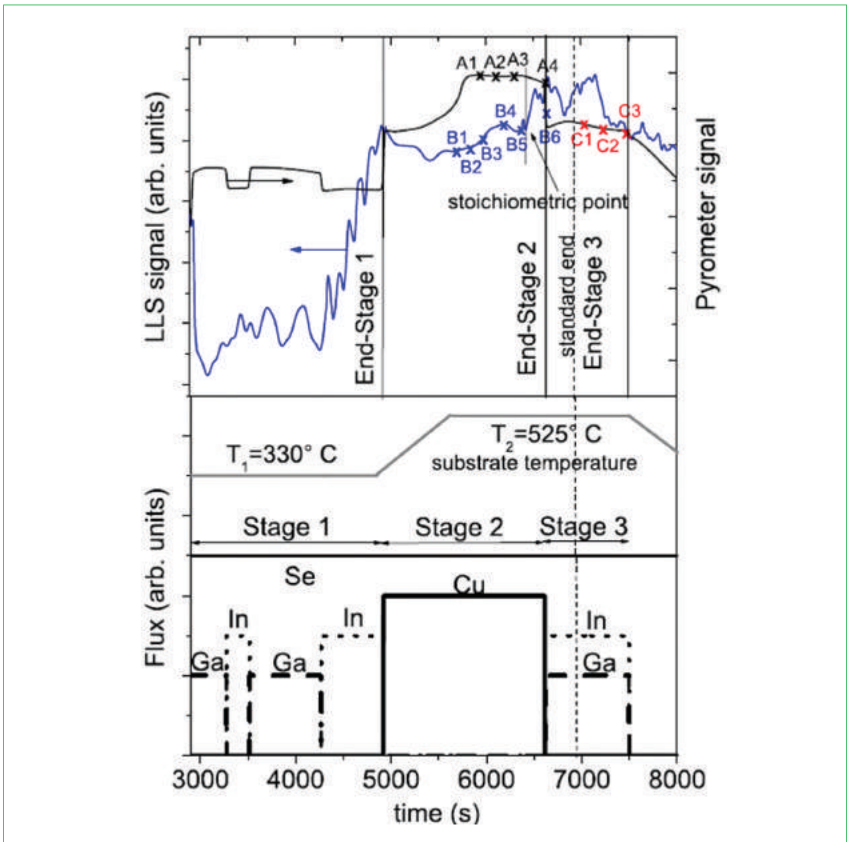

Figure 3. Three-stage co-evaporation process profile: (top) laser-light-scattering signal; (middle) temperature profile; (bottom) elemental flux rates. (From Caballero et al. [12].)

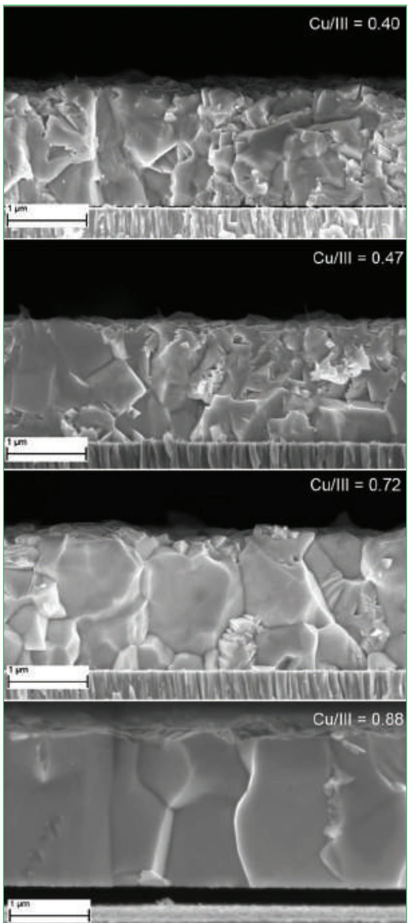

Figure 4. Cross section of CIGS layers with different Cu/III ratios [12].

be used in combination with a standard Mo target in a sputtering system. But Cu-doped with Na and Na_2SeO_3 layers are also used. As a barrier layer, a SiO_xN_y layer is deposited onto the glass before the Mo back contact. During module production it is important to take special care not to damage the barrier layer, because a defective barrier will be an additional source of Na and might affect the CIGS absorber process.

Standard soda-lime glass, however, is limited in terms of the maximum temperature that can be applied during the growth process. Within the ComCIGS research project, HZB and Schott AG tested a new Na-containing high-temperature resistant glass as a substrate. Solar cells processed on the high-temperature resistant glass achieved 19.4% efficiency [7] – a gain of 1.6% absolute compared to solar cells processed onto standard float glass in the same process. It was mainly the electronic properties that improved, as observed by an increase in open-circuit voltage of about 90mV, but also the Ga distribution changed from a graded profile to a flat distribution.

In the case of foil substrates, Na always has to be supplied during the absorber formation. During the last few years, extensive research has been undertaken on the deposition of CIGS onto polyamide (PI) foils. Here, an additional challenge presents itself: PI foils can only withstand temperatures below 420°C without damage. Caballero et al. [8] carried out a study on the influence of the NaF precursor thickness on the device performance at a deposition temperature of 420°C. One result of this study was that Na reduces the In-Ga interdiffusion and decreases the absorber grain size. To achieve optimal device performance the amount of Na has to be carefully chosen depending on the process temperature and the Cu content of the film. Even higher efficiencies on PI foil of 18.7% were achieved by Chirilă et al. [9] at the Swiss-based research institute EMPA. They found that NaF deposition prior to the evaporation process leads to a stronger Ga gradient and therefore lower open-circuit voltages than when NaF is deposited in the last stage of the deposition process; the importance of the Ga profile will be discussed in the next section. Unfortunately, for highly efficient low-temperature processes, the process time increases significantly to more than 60 minutes.

CIGS absorber formation – the key to success, but no golden rule

As mentioned in the introduction, there are two different ways of forming the CIGS absorber layer: 1) co-evaporation of the elements and 2) annealing of a metal precursor in a chalcogen atmosphere. The co-evaporation process, which has led to the highest solar cell efficiencies so far of 20.3% [10], will be discussed first. In Fig. 3 the profile of a state-of-the-art three-stage co-evaporation process is illustrated, as first published by Gabor et al. [11].

The three stages are defined by the fluxes of the elements and the substrate temperatures (all process steps are performed in the presence of selenium vapour and in a high-vacuum chamber):

1. InSe and GaSe layers are sequentially deposited.
2. InSe/GaSe multi-stack is transformed into chalcopyrite by supplying Cu.
3. Shortly after the transition from Cu-poor (Cu/III < 1) CIGS absorber layer to Cu-rich (Cu/III > 1), the Cu source is closed and the In and Ga sources are activated again, to achieve a Cu-poor stoichiometry.

The transition from the Cu-poor to Cu-rich phase is necessary in order to achieve the so-called recrystallization. The grains look larger, as revealed by the scanning electron microscopy (SEM) images of a CIGS cross section presented in Fig. 4, and the electrical properties improve after this step.

To avoid $CuSe_x$ formation it is crucial to switch back to a Cu-poor absorber

layer. An in situ technique called 'laser-light-scattering' has been developed at HZB that allows the detection of the transition very precisely [13]. The excess Cu during the second stage increases the interdiffusion of In and Ga [14] at temperatures about 470°C, as Rissom et al. found out by time-resolved energy-dispersive X-ray diffraction (EDXRD) experiments at the EDDI beamline located at the Berlin synchrotron radiation source BESSY. A growth model proposed by Caballero suggests that at the beginning of the second stage a vacancy compound is formed and that Na occupies the In_{Cu} or Ga_{Cu} antisite. Small grains are formed at the beginning of stage two, and Na is mainly found at the grain boundaries. As soon as the chalcopyrite phase dominates, Na concentration is highest on the film surface, allowing the growth of the grains in the Cu-In-Ga-Se layer. Large grains and a columnar structure are achieved at Cu/III = 0.70–0.95. However, the mobility of Ga atoms is reduced with increasing Cu content, leading to a single Ga gradient with an increased accumulation at the Mo back-contact layer. Progressing to a Cu-rich composition pushes Na to the surface and the back-contact interface. The deposition of In-Ga-Se during the third stage leads to an increase in Ga concentration at the film surface, creating the so-called V-shape Ga gradient as shown in Fig. 5, which is beneficial for device performance. The final CIGS composition should have a CU/III = 0.8–0.9.

> "In the case of sequential processing, the control of Ga is much trickier."

In the case of sequential processing, the control of Ga is much trickier. Because Ga is liquid at temperatures close to room temperature, the Ga has to be supplied via a Cu:Ga target when magnetron sputtering is used for precursor deposition. Today, Cu:Ga targets with up to 30% Ga are available, so that in general the same Ga concentration as for highly efficient co-evaporated CIGS solar cells can be achieved. Unfortunately, it is not possible to tune the Ga distribution within the film as easily as in the case of co-evaporation. Moreover, the Cu content of the film is closely related to the Ga content.

Other options are the use of CuInGa (CIG) targets plus a Cu target to adjust for the Cu/III ratio. CIG targets currently offer lower Ga concentration than CuGa targets. During the annealing process – regardless of whether it is a short or long process and whether Se is supplied via an elemental layer onto the metal precursor layer or via H_2Se – the Cu becomes mobile and forms $CuSe_x$, both of which are essential for grain growth of the CIGS layer. This process leaves behind Ga at the Mo back-contact layer and often no Ga is found at the surface of the CIGS layer. Only long-term annealing at high temperatures will lead to an interdiffusion of the Ga- and In-rich phases. Most companies using sequential processing therefore add a sulphurization step after the selenization. Sulphur increases the band gap of the CIGS semiconductor material and therefore has a similar effect to increasing the Ga concentration. It is important here to have a CIGS layer with low Se content to allow sulphur diffusion in the top layer of the CIGS film. The actual reaction pathway

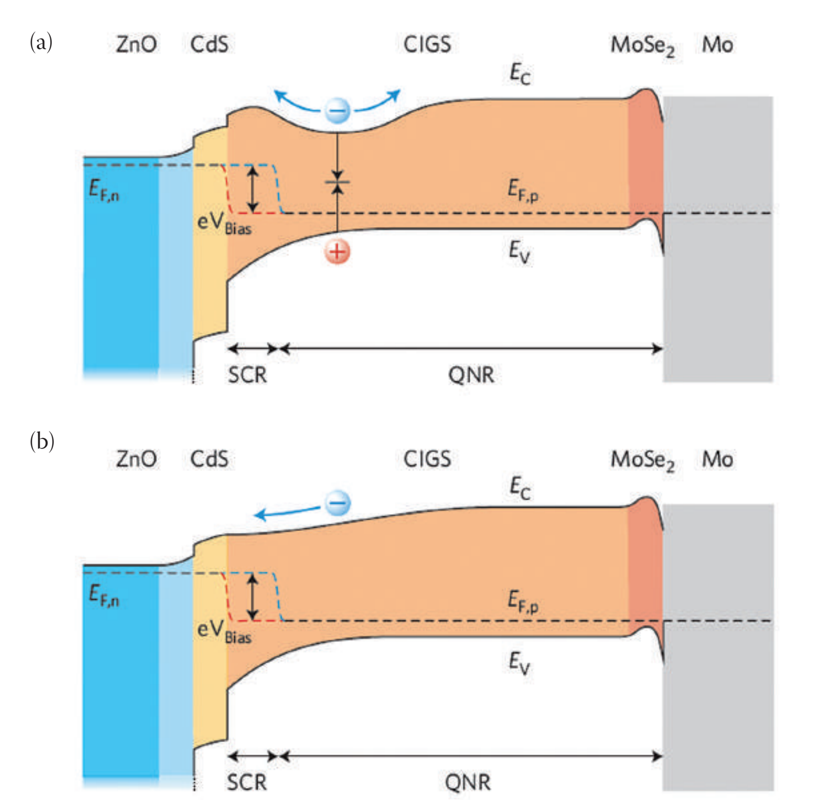

Figure 5. Band structure of a CIGS solar cell (a) with V-shape Ga gradient and (b) without. (From Chirilă et al. [9].)

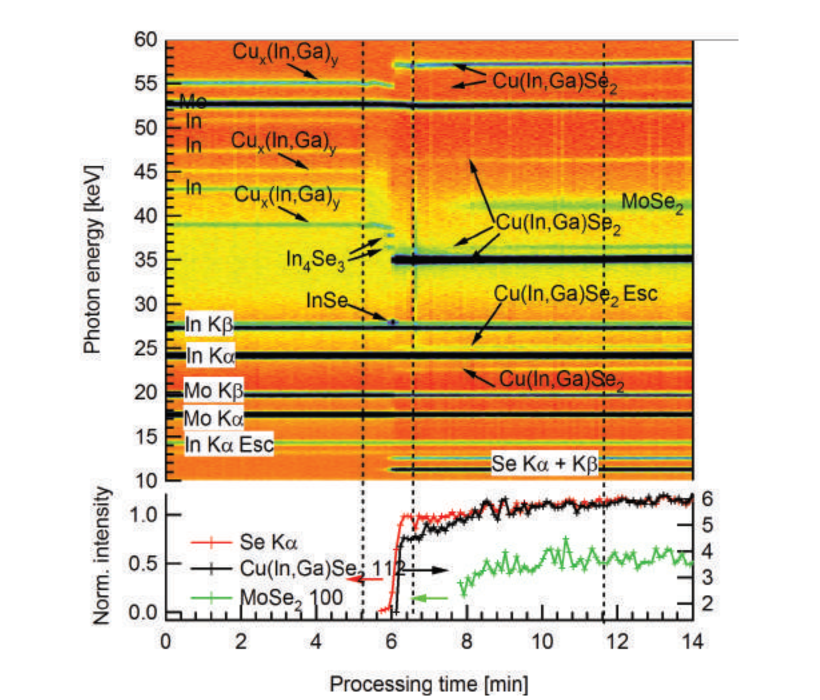

Figure 6. Time-resolved EDXRD and XRF data for the selenization process.

Thin Film

depends on the process conditions and will be discussed later.

Along with sputtering the metal precursors, electrodeposition and ink printing of metal or metal-selenium precursors, mainly using roll-to-roll processing, is currently being investigated and developed by a few companies. The goal is to achieve a non-vacuum process approach for manufacturing CIGS solar modules, but up to now no successful non-vacuum ZnO process which is compatible with the requirements of CIGS material has been found.

To study the reaction pathway during the formation of chalcopyrite layers, intensive research has been carried out at HZB at the EDDI beamline of the synchrotron facility BESSY, which offers the possibility of recording time-resolved EDXRD and X-ray fluorescence (XRF) data with a five-second resolution (Fig. 6). Weber et al. [15] investigated the formation of $Cu(In,Ga)Se_2$ layers from a metal precursor with Cu/III = 0.8 and Cu and Ga sputtered from a $Cu_{0.85}Ga_{0.15}$ which were heated up to 600°C in an evacuated graphite box. Selenium was introduced by means of selenium particles, which melt during the heating-up phase and establish a selenium atmosphere within the graphite box.

From these results the following reaction pathways are derived. The reaction starts at room temperature from crystalline In and at least one $Cu_x(In,Ga)_y$ phase (either $Cu_{16}(In,Ga)_9$ or $Cu_9(In,Ga)_4$). An In-melt is formed around 150°C, and the $Cu_x(In,Ga)_y$ phase becomes more Ga-rich, resulting in a reduced d-spacing of the lattice. Between 200°C and 400°C, InSe and In_4Se_3 are formed. No traces of $Cu_{2-x}Se$ are detected, which is in contrast to the results of Kötschau et al. [16] using a similar technique but with a different precursor (Cu/III = 0.89, $Cu_{0.75}Ga_{0.25}$ target and elemental Se on top of the metal precursor) and an atmospheric pressure process. This finding is also in contrast to the proposed necessity of $Cu_{2-x}Se$ for forming large grains. At temperatures above 400°C, the $Cu_x(In,Ga)_y$ decompose into $Cu(In,Ga)Se_2$ within approximately ten seconds. Break-off experiments showed that the resulting chalcopyrite layer consists of two separate layers: a Ga-rich layer close to the Mo back contact and an In-rich layer at the surface. Solar cells made from this material therefore yielded a relatively low V_{oc} = 536mV but an efficiency of 14.2%, which is quite good for sequentially processed CIGS solar cells without any sulphur.

PVcomB will be looking further into the optimization of the sequential processing of CIGS solar cells using an in-line RTP furnace which operates under a nitrogen atmosphere and has controllable Se and S sources based on the evaporation of elemental Se and S.

Conclusion: how research will help to overcome the hurdles in mass production of CIGS solar modules

To help in achieving a successful mass production, research institutes will aim to deliver in situ process control tools such as laser-light-scattering – the clarification of process pathways by in situ measurements at advanced analytical facilities for optimizing 1) process windows and 2) deposition systems.

In addition, a better understanding of metastabilities (light-soaking effects) of CIGS cells (not covered in this article) will be necessary. Last, but not least, new deposition methods for highly efficient solar cells and low-cost production will need to be conceived. This is being addressed by joint research initiatives such as PVcomB, who are testing new lower-cost deposition methods (for example atmospheric pressure RTP ovens, elemental selenium and sulphur sources, and alternative buffer layer materials and deposition techniques) and laser patterning during monolithic integration.

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About the Author

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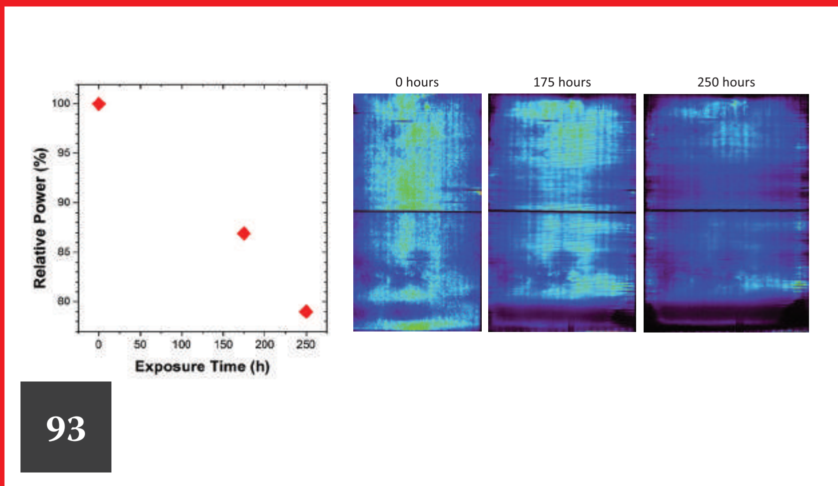
PV Modules



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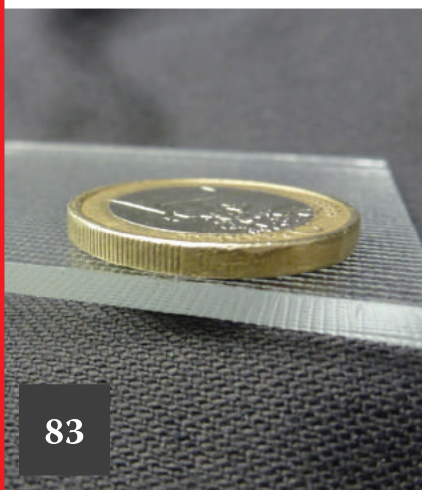

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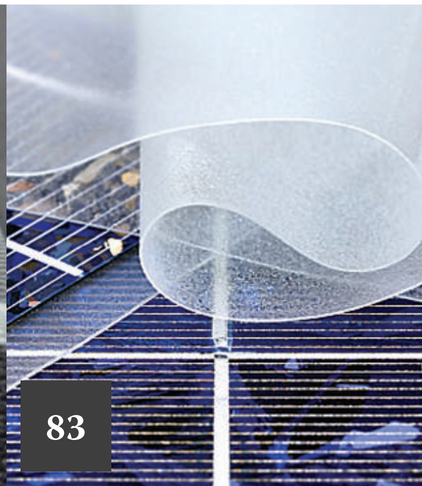

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News

JA Solar to change ADS ratio

JA Solar Holdings has announced that, effective from December 10, 2012, the company's ratio of American Depositary Shares (ADS's) to ordinary shares will change to reflect one ADS representing five ordinary shares.

The solar cell manufacturer has been operating with a ratio of one ADS share to one ordinary share up to this time. However, after receiving notice on October 11 from the NASDAQ Stock Market that its ADS closing bid price for 30 consecutive business days no longer met the requirements for the minimum bid price, JA Solar is looking to boost share price in order avoid delisting.

Each shareholder of record at the close of business on December 10 will be required to exchange every five ADSs held for one new ADS. The company maintains that there will be no change to its underlying ordinary shares.

Further details will be provided to NASDAQ and other market participants before November 26.

Source: bfishadow

JA Solar is looking to boost share price in order to avoid delisting on the NASDAQ.

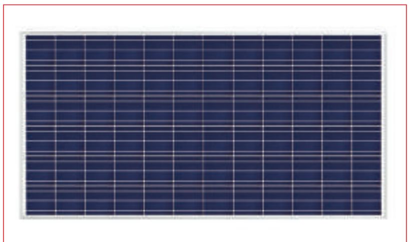
Business News Focus

Trina Solar cuts Q3 shipment guidance and gross margin to zero

Overcapacity, "irrational" pricing of some competitors and a non-cash inventory write-down have forced Trina Solar to lower its module shipment guidance and gross margins for Q3.

Module shipments are expected to be in the range of 375MW to 385MW, compared to previous guidance of between 450MW to 480MW.

Trina Solar said in a statement that it would "confirm or revise" module shipment guidance for 2012 during its Q3 conference call on November 20, before the US stock market opens. Trina Solar had previously revised shipments of between



Source: Trina Solar

Module shipments are expected to be in the range of 375MW – 385MW.

1.75GW and 1.8GW.

The company also said that its gross margin would be impacted by a non-cash inventory write-down and a reversal of prior provisions for anti-dumping and countervailing duties in the US. This would result in margins of between 0% and 1.5%, compared to previous guidance of margins in the middle-single digits range.

Canadian Solar named one of North America's 500 fastest growing companies

Manufacturer Canadian Solar has been ranked 176th by professional service organisation Deloitte & Touche in its 500 fastest growing technology, media, telecommunications, life sciences or clean technology companies ranking for North America.

The list, known as the Technology Fast 500, ranked both public and private companies in North America. Companies were selected based on percentage of fiscal year revenue growth from 2007 to 2011 and were eligible for recognition as long as they owned proprietary intellectual property or technology that was sold to customers in products that generated a majority of its operating revenues.

Deloitte said that the 2012 Technology Fast 500 companies saw revenue growth ranging from 128% to 279,684% between 2007 to 2011, with an average growth of 2,774%.

REC Solar celebrates 15-year anniversary

US-based PV installer REC Solar is celebrating its 15-year anniversary this week.

Over the company's 15 years in business, REC Solar has installed 118MW of solar, consisting of over 8,700 installations in 16 states, ranging from California and Colorado to New Jersey and Florida.

In the past year REC Solar has posted rapid growth, with nearly five times as many megawatts installed last year alone as in its first 10 years of business. The company has more than 800 employees with 17 offices in six states and is a subsidiary of Mainstream Energy Corporation.

Fifteen years in business represents unusual longevity for the solar industry. GTM Research Analyst Andrew Krulewitz commented: "The solar industry has proven highly volatile for both manufacturers and installers. Though demand for solar has grown tremendously in the past few years, the industry landscape has become increasingly competitive. We're now seeing a shakeout of less-competitive firms at all points on the value chain."

The company boasts good customer relations with business from Main Street, farms and ranches, government agencies including the Departments of Defense, Veterans Affairs and Agriculture, large multi-national businesses including Costco, IKEA, Nestle and DuPont and thousands of homeowners across America.

Trina Solar revises down full-year shipments as Q3 sales and revenue fall

Tier 1 PV module manufacturer Trina Solar has reported revenue of US$298 million, down 13.9% compared to the previous quarter.

The company indicated that Q4 2012 module shipments would be flat to slightly up at between 380-400MW, compared to Q3 2012 shipments reported as 380MW.

Trina Solar also revised down full-year shipment guidance to between 1.55GW to 1.6GW, compared to previous guidance of 1.75GW to 1.8GW.

The company made a net loss in the quarter of US$57.5 million, compared to US$92.1 million in Q2 2012.

Gross margin was reported at 0.8%, compared to 8.4% in Q2, due primarily (4.5% impact) to inventory write-downs in connection with the decreasing average selling price of modules.

With market conditions expected to remain unchanged, Trina Solar gave a guide gross margin for Q4 to close to that of Q3.

Source: REC Solar

Over the company's 15 years in business, REC Solar has installed 118MW of solar, consisting of over 8,700 installations in 16 states.

Innotech Solar celebrates three years with no hot spots on modules

Solar manufacturer Innotech Solar reports that it has gone three years with its solar module production free from any hot spots.

The Norwegian company acknowledged that hot spots increase the temperature of solar panels, which can lead to loss in the yield of a PV system and, in some rare cases, the module erupting in flames.

Centrosolar sales up in Q3, year-end revenue guidance down

Centrosolar reported its core downstream business of rooftop installations increased 29% in Q3 2012 as sales in Italy, Belgium and North America improved.

Module sales in the quarter increased 29% quarter on quarter to 32.6MW and 12% (98.6MW) for the first nine months of the year. International sales reached 72% of revenue for the first nine months of the year, up from 62% in the same period a year ago.

However, the company reported revenue of €55.5 million, down 24% from the same quarter last year when revenue reached €72.9 million. The revenue fall was said to be due to a fall in PV project sales and module ASP declines, which the company said had fallen 37% in last 12 months.

Sales were also impacted by the bankruptcy of several of its solar glass segment customers. Solar glass sales were also impacted by lower demand as module manufacturers cut production, a trend expected to continue in Q4 on the back of weaker seasonal demand.

Overall, Centrosolar reported EBITDA of -€4.2 million.

CASE accuses SolarWorld of inaccuracy

The Coalition for Affordable Solar Energy (CASE) released a statement in October 2012 to clarify the anti-dumping duties levied on Chinese solar manufacturers.

With regards to the figures in SolarWorld's press release, Jigar Shah, President of CASE, said: "These numbers were wrong on October 10 and they are wrong today."

He continued: "CASE would like to clarify the Department of Commerce's ruling today on the AD and CVD tariffs

Source: SolarWorld

SolarWorld was accused of inaccuracy by CASE.

for imported Chinese solar cells. It is clear that there is confusion around the decision, specifically around the required 10.54% reduction in the AD rate to avoid double counting of anti-subsidy tariffs.

"All the final AD decisions have decreased significantly," he said.

STR Holdings sales continue to fall in 2012

Overcapacity and weak demand continue to impact sales at PV encapsulant material supplier, STR Holdings.

Net sales were US$23.1 million in Q3, down 8.1% sequentially and 58.9% from Q3 2011. The company said that Q4 sales would be in the range of US$14 million and US$16 million.

The company noted that PV encapsulant material volume sales had declined by approximately 45% in the last 12 months, while ASPs declined by approximately 20%.

Net loss from continuing operations for the third quarter of 2012 was US$3.6 million.

Robert Yorgensen, STR's President and Chief Executive Officer, said: "We believe that demand has softened considerably throughout the industry on the heels of negative policy revisions, primarily in Italy and Germany, and our sequential volume reflects this.

"We continue to execute our strategic objectives of reducing our cost structure and developing innovative products. The launch of our next-generation encapsulant is progressing well with favorable results obtained from our internal testing and the successful completion of damp heat testing with several prospective Chinese customers."

Source: AMagill

Overcapacity and weak demand continue to impact sales at PV encapsulant material supplier, STR Holdings.

Yorgensen noted in a conference call to discuss financial results that the company was close to securing the first supply contracts for the new EVA encapsulants, with volume ramps expected in early 2013. Over 20 module manufacturers were evaluating the product, according to Yorgensen.

Testing and Certification News Focus

Solarwatt module tops TUV Rheinland energy yield test

Germany-based Solarwatt's M250-60 AC 245Wp module has come top in the TÜV Rheinland "Energy Yield Test 2011", which tests the performance of solar modules from different manufacturers.

The modules were tested for a year under outdoor installation conditions and were regularly checked for energy yield and other properties, such as degradation.

Solarwatt's module exceeded its performance promise — although the label stated 245Wp, the module achieved 246.73Wp according to the company's own measurements. TÜV Rheinland measured an output of 246.5Wp.

The module also achieved a low degradation value of 0.2%.

CNPV modules pass PID testing at Intertek

Monocrystalline and multicrystalline modules from CNPV Solar Power have successfully passed Potential Induced Degradation (PID) certification evaluation IEC62804, tested by Intertek.

CNPV said that under the IEC 62804 standard, Intertek had observed 0% degradation during the tests, which included test conditions of 60 degrees Celsius, 85% relative humidity, a negative 1,000V DC charge for a continuous period of 96 hours.

However, the company also undertook further tests which included raising the temperature to 85 degree Celsius and keeping other test parameters and extending the test duration to 480 hours.

The company said that under these more extreme conditions, degradation was well below 0.3%, potentially setting a new crystalline class standard.

First Solar modules certified to meet UL 1703 standards for systems up to 1000V

First Solar has advised that its thin-film Series 3 PV modules have met the standards and, therefore, been listed by Underwriters Laboratories for UL1703 and ULC1703.

The certification allows the modules to be used in PV systems up to 1,000V. Previously, the modules were UL listed as meeting the 1703 standards for use in PV systems up to 600V.

"First Solar is pleased that UL has validated the quality and safety of our modules, which are the first thin-film PV modules to receive this certification," said Tom Kuster, First Solar vice president of product management and system technology.

Phono Solar modules confirmed for UL1703 standard

Phono Solar's mono- and polycrystalline solar modules were tested and certified by Intertek for conforming to UL1703 standards.

The certification allowed for Phono Solar's tested modules to additionally be ETL certified, which verifies their capacity to receive 1000V of maximum system voltage.

The company noted that both certifications are indication that the modules are suitable for use in high-voltage, large-scale power plants.

PV Modules Order Focus

China Sunergy provides modules for 3MW plant in Romania

Solar cell and module manufacturer China Sunergy's (CSUN) has supplied its 240-60P multi-crystalline modules for a solar plant in Romania.

Source: China Sunergy

China Sunergy's multicrystalline modules were used in one of the latest PV projects in Romania.

Developed by Sunergy's Czech partner Alufront, the 3MW solar park is located near Brasov.

Stephen Cai, CEO Of Sunergy, said that the use of CSUN's solar modules represents the company's plan to broaden and diversify its revenue base.

Canadian Solar supplies modules for Turkey PV project

Canadian Solar has delivered its CS6P-P solar modules for Turkey's 540kW solar project, which was built at the Izmir airport.

The project is the first to be built under Turkey's new energy legislation law for solar power plants under 500kW. The ground-mounted project is the largest solar plant in the country and the first to be built at an airport in the region. The 540kW installation features 450kW on-grid and 90kW off-grid. Gehrlicher Merk Solar contributed as the engineering, procurement and construction manager for the project.

ReneSola offers locally produced PV modules for Indian market

Chinese module and wafer manufacturer ReneSola has started to provide locally produced PV modules outside of China for the first time by offering India-made PV modules to the Indian market.

Based on the current demand of solar panels in India, the company is expecting to supply 250MW of made-in-India PV modules to its Indian customers over the next two years. In order to meet this target, the company will collaborate with local strategic partners.

India has been identified as an important market for the company and the move is in line with ReneSola's sales and marketing strategy in the country.

"Considering the strong and growing demand the India PV market presents for electricity, coupled with the government's strong support and generous subsidies for solar energy, ReneSola considers India to be a key market within Asia," said Stephen Huang, APMEA President at ReneSola.

ReneSola has also announced that it has introduced its new Virtus II multicrystalline modules to the Indian market at the 6th Renewable Energy India 2012 Expo, a three-day event held in New Delhi this week. The introduction follows the successful launch of the product in the US and Australia.

Spire shipping first blue light enhanced sun simulators in Q4

PV equipment supplier Spire Corporation is shipping the first of its Spi-Sun Simulator 5600SLP units, which use enhanced blue light technology for advanced solar cell/module performance measurement.

Spire said it had at least one of the new sun simulators, its core product line, shipped in the third quarter of 2012, while further shipments were expected in the fourth quarter to customers in China.

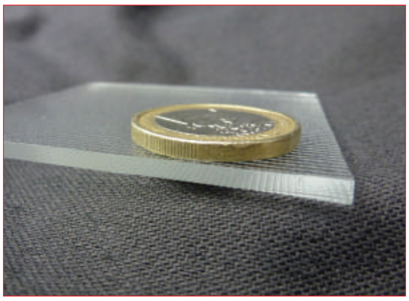
The company revealed in its Q3 2012 SEC financial filing that it had deferred cost of goods sold of US$94,000, which related to equipment shipped but revenue not recognised. Spire also had US$2.3 million allocated to work in progress and finished goods valued at US$1.2 million at the end of Q3.

Source: Spire Corporation

Spire Corporation is shipping the first number of Spi-Sun Simulator 5600SLP.

Product Reviews

Centrosolar Glas



Centrosolar Glas offers 30% reduction of module glass thickness and weight

Product Outline: Centrosolar Glas has developed a thin solar glass for photovoltaic modules. The CENTROSOL thin glass is only 2.3mm or 2.6mm thick, enabling a reduction in the minimum thickness by almost 30% at the same mechanical resistance, thanks to process optimization. The thin glass is claimed to simplify assembly, and transportation and mounting costs.

Problem: Reducing module weight and providing enhanced technologies that make conventional PV module glass 'smart' supports both enhanced yield and lower BOS costs during installation.

Solution: The CENTROSOL thin glass also offers the advantage of higher light transmission. It also extends the operating life of PV modules because glass is more resistant to environmental effects than a plastic backsheet. The thermal conductivity of glass is higher than a backing film, reducing the cell operating temperature of a glass-glass module and improving efficiency, especially in hot climatic conditions. The company also claims that a 6% increase in the annual energy yield is attainable from photovoltaic modules, which is made possible by a patented anti-reflective coating that minimizes reflection by the surface of the glass, thus maximizing energy transmission to the solar cell or absorber.

Applications: Suitable for glass-glass modules.

Platform: The energy yield can be further increased by means of the CENTROSOL HiT Nano Power anti-reflective coating. This coating further improves the transmission properties and therefore the annual energy yield of a photovoltaic system by up to 6 %.

Availability: August 2012 onwards.

Dunmore Corporation

Dunmore's 'DUN-SOLAR' TPE backsheet meets latest 25-year warranty needs

Product Outline: Dunmore Corporation has developed a new version of its 'DUN-SOLAR' TPE solar module backsheet. TPE provides the proven performance of DuPont 'Tedlar' polyvinyl fluoride film in a construction that exceeds current market requirements for longevity and total cost of ownership.

Problem: With warranty periods on solar modules extending to 25 years and beyond, manufacturers are seeking high-performance components that will not cause premature failure or performance loss. At the same time, they need to keep their costs low so solar energy can compete with the price of established energy sources.

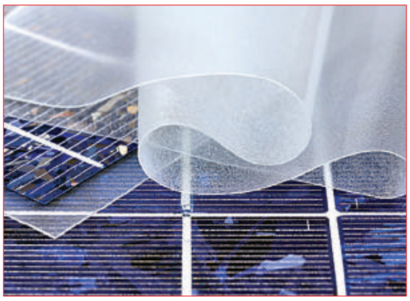
Solution: The new TPE backsheet made with improved materials extends solar module lifetime and productivity because they better protect the solar module's circuitry from moisture and performance loss. More durable insulation also protects workers from electrical shocks while they are maintaining solar modules. Dunmore engineered this advanced backsheet using the latest Tedlar-oriented polyvinyl fluoride film, and improved polyester core and adhesive materials. Now DUN-SOLAR TPE offers damp heat performance beyond 3000 hours at more competitive pricing.

Applications: PV module backsheet integration via the lamination process.

Platform: DUN-SOLAR TPE is among the first UL-listed backsheets that incorporates the latest Tedlar-oriented polyvinyl fluoride film. PV manufacturers looking to start using the the next generation TPE can take advantage of Dunmore's 'SmoothStart' engineering services programme. The SmoothStart programme places one of the company's engineers on the customer's production floor at no additional cost.

Availability: Will be in full production starting in Q3, 2012.

Wacker



Wacker's TECTOSIL encapsulant offers PID protection

Product Outline: A thermoplastic encapsulant from Wacker, TECTOSIL has proved to offer protection against potential-induced degradation (PID), according to tests carried out by Photovoltaik-Institut Berlin. The testers confirmed that such modules do not display leakage currents due to PID when using the thermoplastic silicone elastomer sheet in the encapsulation of PV modules.

Problem: PID is caused by undesired leakage currents on the cell surface. They cause negative charge carriers that would normally flow to the cell's back contact to be discharged via the encapsulation and module frame, unused. Penetrating moisture and high module voltages promote this type of discharge, which can cause considerable performance losses. However, the PID effect is reversible and can be restricted through technical countermeasures.

Solution: Measurements by the Photovoltaik-Institut Berlin have shown that such PID effects can be effectively suppressed, or prevented, with TECTOSIL encapsulant, which was tested as per IEC standard 60904-1 at a system voltage of 1,000 volts. The modules encapsulated with Wacker's material showed no signs of PID, either in their voltage characteristics or during subsequent electroluminescence analysis.

Applications: Module encapsulation.

Platform: TECTOSIL is a flexible, highly transparent and electrically insulating sheet comprising an organosilicone copolymer. Because of its thermoplastic properties, the silicone-based polymer can be processed quickly and inexpensively – without curing or other chemical reactions, which facilitates short cycle times and a high tolerance to local temperature differences within the laminator.

Availability: September 2012 onwards.

Product Reviews

Ecoprogetti

LED-based sun simulator from Ecoprogetti offers high repeatability in compact size

Product Outline: Ecoprogetti's triple class A sun simulator ECOSUN 10L represents a new generation of sun simulator which employs LEDs as the light source for greater comparison with real-world conditions.

Problem: Conventional Xenon lamp-based sun simulators do not adequately cover the full spectral range from 365-1080nm, limiting the conditions a PV module will experience in the field. Long lifetime and low power consumption requirements have also restricted Xenon lamp-based systems' ability to reduce CoO.

Solution: The ECOSUN 10L can extend the impulse duration to more than seven seconds, a feature that excludes the phenomenon of capacitive effects. The unit is also usable on next-generation, high-efficiency cells, low-loss junction boxes as MOSFET and modules with micro inverters. A stable, repeatable and constant pulse allows users to measure in a very repeatable and reliable way the power of a module with a repeatability error of less than 0.2% on more than 100 measurements, according to the company. Another benefit of using LEDs is the long lifetime, which can be expressed in 30 millions of tests , compared to 50 thousand flashes of a Xenon lamp of sophisticated level.

Applications: Triple A class for testing of PV modules, including crystalline, thin-film and back-contact solar cell modules.

Platform: The simulator's very compact footprint of 4.6m² and its work height of 1,000mm makes it suitable for an in-line production and for factories and laboratories with limited space. TUV Intercert performed an in-depth control before characterizing the unit and releasing the certificate of triple A class.

Availability: Currently available.

Mondragon Assembly

Mondragon's TS 1200 tabber and stringer provides high throughput and versatility

Product Outline: Mondragon Assembly has launched the new Tabber & Stringer TS 1200 Plus, with a net capacity of 1,300 solar cells soldered per hour. Mondragon believes the new system is one of the fastest and most versatile combined tabber and stringers available on the market.

Problem: Module manufacturers are constantly seeking ways to reduce costs and increase efficiency.

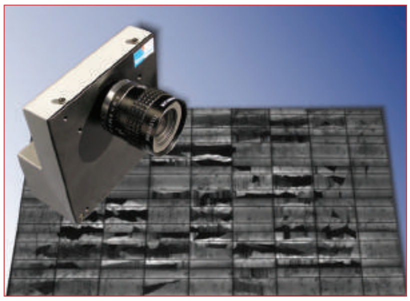
Solution: The machine forms strings of cells which are automatically available in their definitive position on the base of the module. The modular-built system is claimed to be robust, flexible and ergonomic, with easy maintenance as well as fast diagnostics. The TS1200 uses an infrared light technology soldering process to offer easy maintenance, model change and diagnosis. Furthermore, TS 1200 PLUS is claimed to have superior cell loading autonomy and has greatly lessened installed power and air consumption.

Applications: Capable of handling 5" and 6" wafers for cell to module assembly.

Platform: The Tabber & Stringer TS 1200 has the following dimensions: (WxLxH):6000mmx3200mmx2500mm; weight: 4000kg. The power consumed is 10kW/h the power installed is 31kW. It needs air consumption of 750Nl/min. The cell handling is through Scara Robot and the cell alignment through vision system (CDD Camera).

Availability: Currently available..

Sensovation



Sensovation's SamBa series low-light cameras are optimized for high-throughput electroluminescence imaging

Product Outline: With the SamBa series of low-light cameras, Sensovation is able to offer sensitivity in the near-IR range at high speed that enables industrial testing applications such as electroluminescence imaging of solar sells and modules. SamBa Ci is a 2MPixel, high-sensitivity camera optimized for high-throughput electroluminescence imaging.

Problem: Electroluminescence imaging of solar modules demands highly sensitive cameras with extremely high pixel resolution. Often there is little room for mounting the camera – therefore short working distance is required.

Solution: Electroluminescence measurement has become a valuable tool in inspection and quality control of solar cells and modules in the photovoltaic industry. Equipped with sensitive, high-resolution, scientific-grade Si-CCD sensors, 16-bit ADCs and powerful 4-stage thermo-electric cooling, the SamBa cameras are ideally suited for high-resolution solar cell characterization. The SamBa Ci and the coolSamBa HR-830 were specifically designed for in-line and off-line production characterization of solar cells and modules. The SamBa cameras provide high sensitivity and exceptionally high spatial resolution but also a high imaging speed of one image per second for the full imaging cycle including read-out and integration time.

Applications: Electroluminescence measurement of photovoltaic cells and modules.

Platform: The frame rate of 3 fps allows a throughput of 1 cell per second. The Samba Ci is available with a robust Gigabit Ethernet interface and comes with a flexible Software Development Kit (SDK) for easy integration.

Availability: October 2012 onwards.

Potential-induced degradation effects on crystalline silicon cells with various anti-reflective coatings

Simon Koch, **Juliane Berghold** & **Paul Grunow**, Photovoltaik-Institut Berlin (PI-Berlin), Germany

ABSTRACT

Because potential-induced degradation (PID) can cause power losses of more than 30% for modules out in the field, there has already been an extensive effort placed on avoiding this adverse phenomenon. A key feature at the cell level is the silicon nitride (SiN_x) anti-reflective coating (ARC). Apart from the known dependency of PID susceptibility on the refractive index, the impact of the deposition parameters has also been under investigation. This paper illustrates the influence of different silicon nitrite layers and their ability to prevent PID. A large number of cells and modules were therefore manufactured, differing only in the type of ARC. The modules were subsequently PID tested under three different climatic conditions, and acceleration factors and activation energies were determined from these tests. In addition this paper presents the results of addressing the weak-light performance and the hot-spot risk of panels after PID exposure. Finally, the reversibility of PID was also investigated in relation to the state of degradation of these samples.

Introduction

Depending on the system configuration of solar installations, significant electrical potentials with negative polarity relative to ground can form between the frame and the solar cells within the modules. The actual potential is dependent on the total system voltage, the inverter type and the position of the module within the string, and could theoretically be as high as 1000V. In the past, this potential could be regarded as the root cause of the observed power losses of photovoltaic systems. The resulting degradation of the system is known as potential-induced degradation (PID) [1].

The common model for explaining the PID effect states that the potential causes the diffusion of positive sodium ions from the glass through the embedding material towards the cell. It is assumed that sodium ions can accumulate in certain regions of the silicon nitride (SiN_x) anti-reflective coating (ARC). In the case of p-type wafer-based silicon cells, these charge centres can generate local shunts in the p-n junction [2,3].

> "It is advantageous to address and resolve PID at the cell level."

Even though there are several ways to suppress the PID that occurs in the field, for the sake of flexibility of panel and system design it is advantageous to address and resolve PID at the cell level. The ARC layer (or layers) has been found to be the key feature with respect to the PID sensitivity of the solar cell.

The sensitivity of solar cells to PID could be minimized by simply increasing the refractive index of silicon nitride, as presented by Pingel et al. [1]. But a suitable refractive index for preventing PID is often not ideal in terms of cell efficiency. Consequently, alternative approaches have had to be identified for suppressing the PID effect. For example, this year at the EU PVSEC, Mehlich [4] put forward the possibility of improving cell resistance to PID through several pretreatment steps during the manufacturing process prior to SiN_x plasma deposition. A major issue with this approach is the impact of the anti-reflective coating itself on the PID effect.

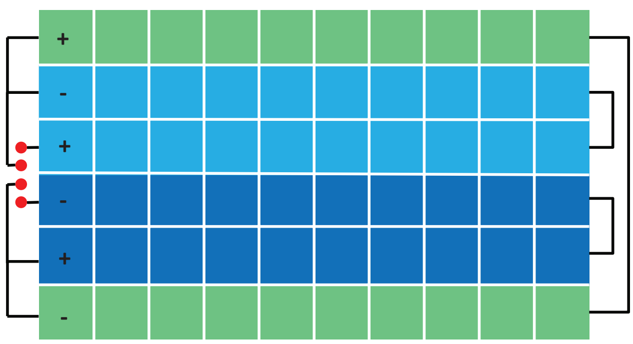


Figure 1. Interconnection scheme of the investigated modules. Each module was realized with three different cell-type strings (green, light blue and dark blue).

The significant influence of different ARCs on the PID stability of the whole module is demonstrated here. Besides the PID test series in which different ARCs are applied, some 'secondary' effects of PID are also presented, specifically the influence of PID on:

- the hot-spot risk of the module
- the weak-light performance

Furthermore, PID is discussed in terms of the influence of ambient conditions; in particular, the acceleration factors for different test temperatures (60°C vs. 85°C) are presented, as well as the reversibility of PID.

Experiment design

Standard industrial, screen-printed, Al-back alloyed monocrystalline p-type Si solar cells were manufactured in a single experiment run by centrotherm photovoltaics AG in an industrial environment, resulting in 21 different cell types. In order to increase the comparability and the statistics, 20 cells of the same type were connected in one string. Three strings with different cells were then connected to one module (Fig. 1). All modules were manufactured at a standard module production site, using an encapsulant material which was known to be prone to the PID effect [5].

Besides the use of an encapsulant

with known susceptibility to PID, low-resistivity wafer material was also chosen intentionally. To evaluate the relative influence of different ARCs, it is undesirable to produce samples which are PID resistant because of other influencing parameters.

Since an official standard has not yet been released for PID analysis (IEC draft 62804 is still pending), the three most common test method proposals have been adopted for investigating the PID behaviour of the different cell concepts. The investigated test conditions are as follows:

1. Climatic conditions of 85°C and a relative humidity (RH) of 85% for 48 hours (PI-Berlin standard).
2. Climatic conditions of 60°C and 85% RH for 96 hours (proposal for the IEC standard).
3. Durability test at 25°C with no specific humidity level control for 168 hours (proposal for a simple PID test set-up published during EU PVSEC 2011 [6]).

As well as the different climatic conditions and durations, all modules were created by means of a continuous metal contact over the whole glass area.

Experimental results

Comparison of double- and triple-layer structures

As mentioned earlier, it is known from earlier results in the literature that an increased refractive index is associated with an increased robustness to PID. This was also confirmed during PI-Berlin's analysis (Fig. 2).

> "An increased refractive index is associated with an increased robustness to PID."

The disadvantage of an increased refractive index is that it results in lower efficiency at the cell level, in particular prior to embedding. Hence, it is of particular interest to determine if it is possible to create double-layer structures which can combine the beneficial effects of layers with high refractive index (high resistance to PID) and layers optimized with regard to low optical losses.

Fig. 3 shows a comparison of four different double-layer cell designs (G–J) and a standard single-layer structure with a refractive index of 2.08 (A). The tested double-layer designs consisted of one layer with a standard refractive index and one

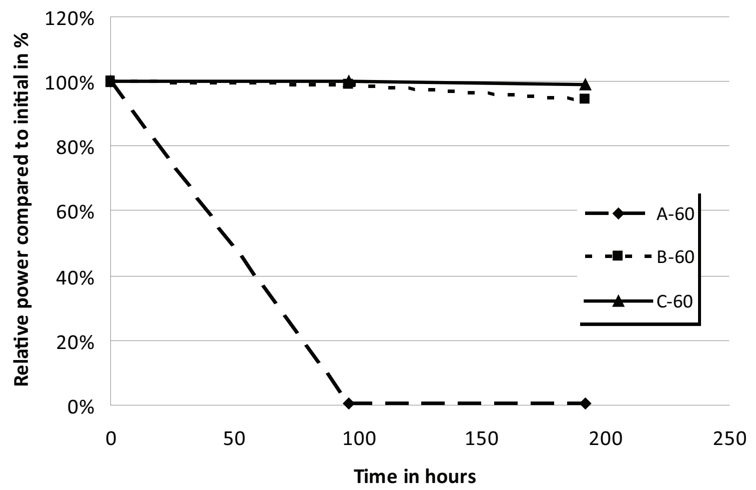


Figure 2. PID results after two cycles of the 60°C/85% test method applied to cells with different refractive indexes (A=2.03; B=2.2; C=2.3).

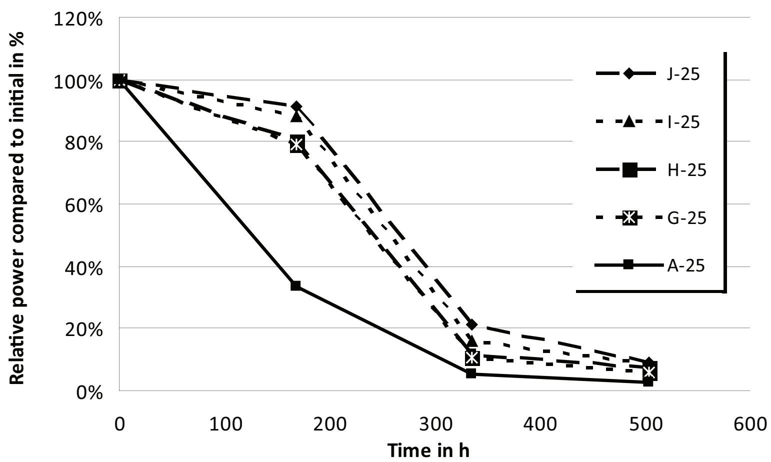


Figure 3. Comparison of the degradation behaviour of various double-layer cells (G–J) compared with standard single-layer cells (A) during the 168-hour/25°C test method.

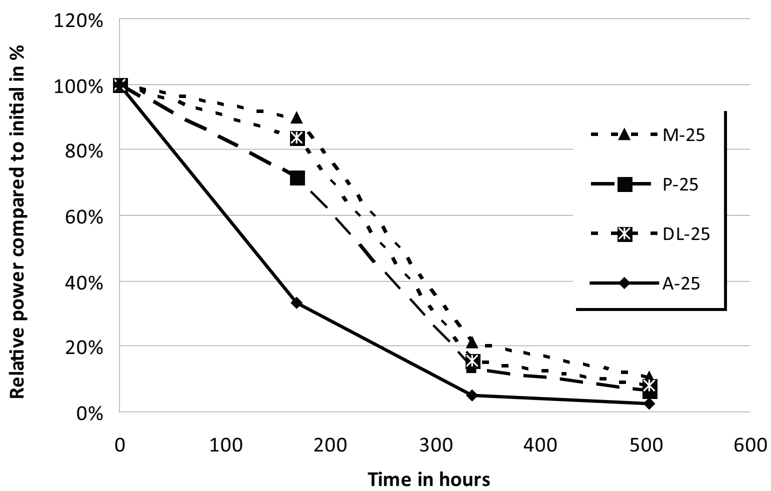


Figure 4. Comparison of the PID behaviour of cells with single (A), double (DL) and triple (M, P) ARC layers during the 168-hour/25°C test method.


UV Exposure degrades
PET over time.

layer with a refractive index ranging from 2.2 to 2.5 (G–J).

As seen in Fig. 3, the application of a second layer slightly increases the resistance to PID but does not effectively prevent it. Nor do triple-layer designs show significant improvements (see Fig. 4) over single-layer ones: the degradation is similar to the average degradation of cells with a double-layer ARC (DL-25). The small impact of multi-layer ARCs is probably due to the limited thickness of the layers with high refractive index, which was restricted in order to avoid undesirable optical losses.

Alternative approaches

In addition to the insertion of additional (double, triple) layers with different refractive indexes, there are other approaches for modifying the ARC. These include the use of modified deposition conditions, a pretreatment by radiation (with or without a process gas), and an additional gas flow. The approaches aim either to suppress the leakage currents at the cell level or to increase the conductivity in order to prevent a charge build-up in the ARC.

Several groups, which included elements of these alternative approaches, were tested in the experimental series. Four of the groups with alternatively modified ARCs are shown in Fig. 5 and compared with group M (best-performing multi-layer ARC – triple-layer), which was illustrated earlier in Fig. 4. The test was carried out at a higher temperature of 60°C and 85% RH because the samples showed no degradation under 25°C conditions. A clear improvement as a result of the modifications was obtained, with the exception of one group. Multi-layer structures are also partly included here, but once again did not prove to be superior.

In summary, it can be concluded that there are various possibilities for modifying the ARC and for improving the PID behaviour of cells. In future experiments, the alternative approaches will be combined and/or modified to further enhance resistance to PID.

Hot-spot risk and PID

It was mentioned earlier that PID can generate local shunts in the p-n junction. This fact leads naturally to the question of what influence these shunts have on the cells in terms of hot-spot generation. To answer this question, one module was prepared in such a way that one string in the module was prone to PID and the other two were stable. The module was initially tested according to the IEC 61215 [7] procedure for determining the hot-spot risk. The key parameter of the risk potential is the level of leakage current at reverse bias of each cell.

No significant difference between the three unequal strings could be seen after the initial hot-spot analysis. The difference

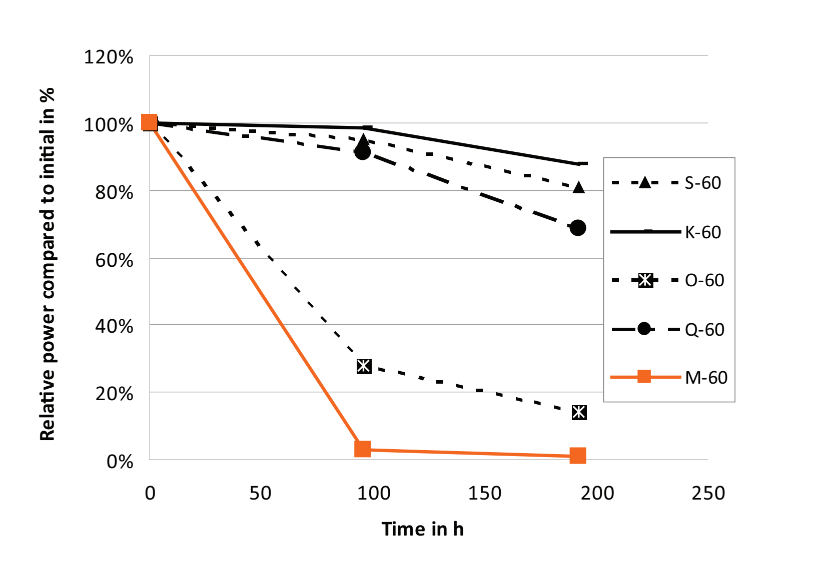


Figure 5. Comparison of the PID behaviour of cells with modified ARC deposition and the best-performing standard triple-layer – M (see Fig. 4). (Test conditions: 60°C/85% RH.)

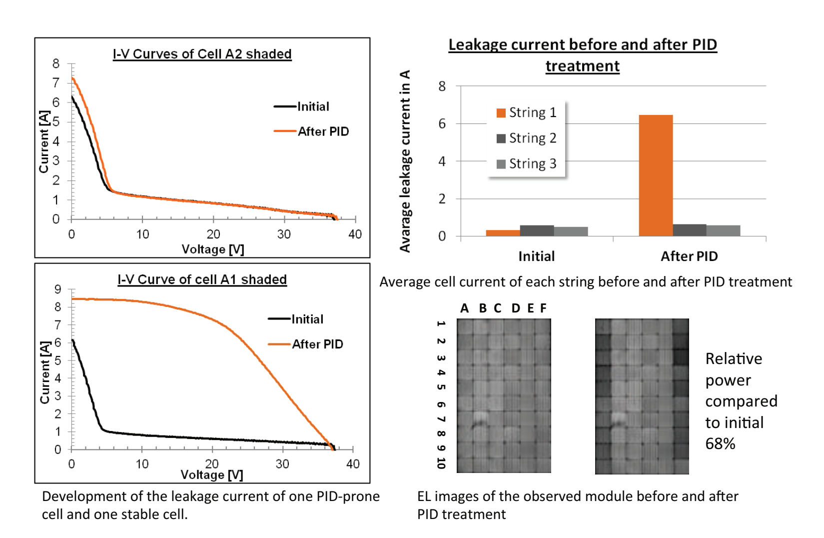


Figure 6. Hot-spot risk analysis before and after PID treatment.

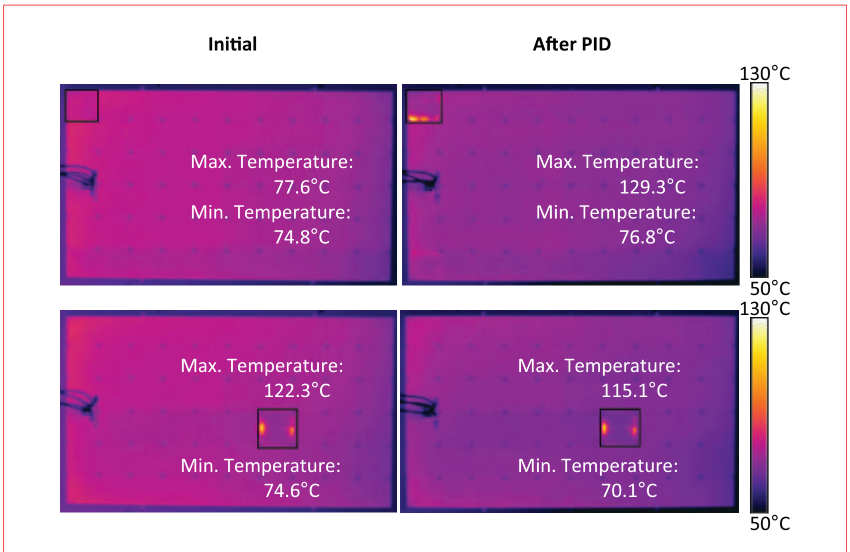


Figure 7. Maximum temperature during a hot-spot test of one PID-prone cell (top) and one stable cell (bottom), before PID degradation (left) and after (right).

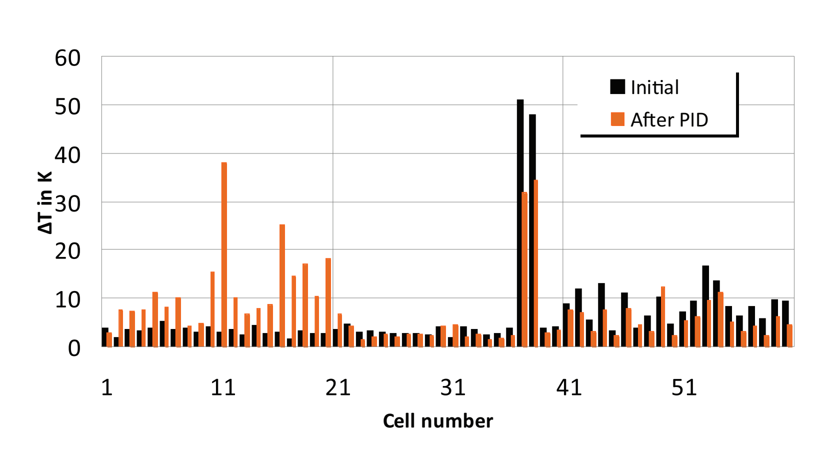


Figure 8. Increase in the temperature difference between minimum and maximum cell temperatures of PID-prone cells (1–20) and PID-stable cells (21–60) during a hot-spot analysis.

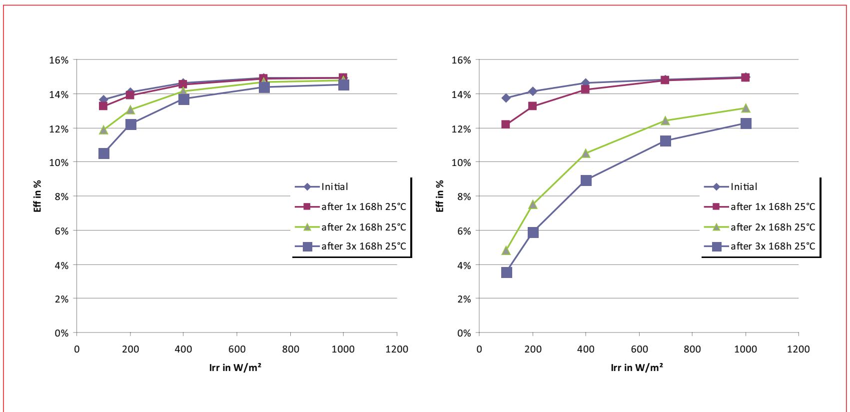


Figure 9. Impact of PID on the weak-light performance of one stable cell string (left) and one prone cell string (right).

in the average leakage current at reverse bias was of the order of around 25%, which is a typical result. After five hours of PID stress, the PID-prone string showed only 68% of the initial power, and the other two strings still showed 99% of their initial values. Performing the IEC 61215 hot-spot analysis again revealed an increase of about 20% in the leakage current at reverse bias for the two stable strings; on the other hand, the prone string showed an increase of about 1846% in leakage current at reverse bias. Fig. 6 shows the significant increase in the average current and two leakage currents at reverse bias changes for the two stable and one PID-prone strings.

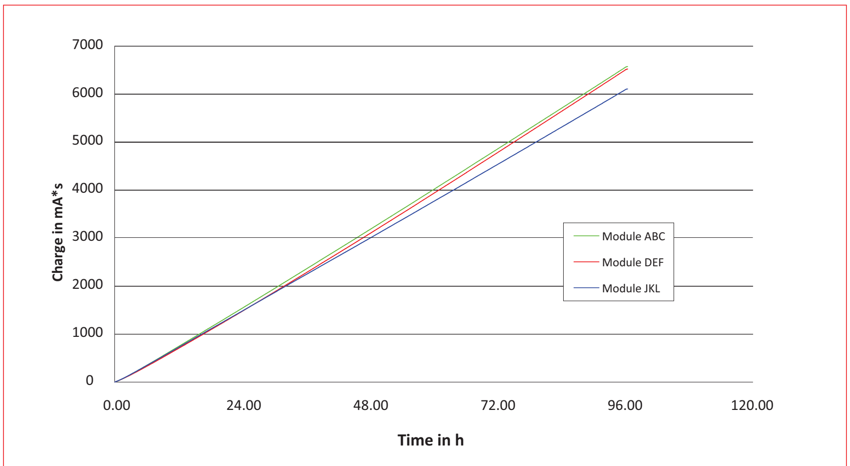


Figure 10. An example of integrated leakage current over time during a PID stress test. Compared to initial STC measurements, the relative powers of modules ABC, DEF and JKL are 66%, 1% and 32% respectively. No link could be found between degradation level and accumulated charge.

In a second step performed according to IEC 61215, the cell with the highest leakage current in reverse bias was shaded and stressed with a sun simulator for one hour. In PI-Berlin's case every cell was shaded for 30 seconds under the sun simulator and the maximum temperature was determined. The detailed procedure and the differences between this and the IEC test were presented by Wendlandt et al. at the 2012 EU PVSEC [8]. The IR images of the worst-performing PID-prone (top) and stable (bottom) cells, before and after the PID test, are given in Fig. 7. A comparison of the images reveals a rapid increase of around 30K in the maximum temperature of the PID-prone cell.

An overview of all 60 maximum cell temperatures before and after the PID treatment is presented in Fig. 8. A significant increase in the temperatures for the PID-prone cells (1–20) can be observed.

These results show that not only do modules which are affected by PID exhibit a power drop, but there is also the risk of them potentially generating hot spots in the field.

Weak-light performance

In addition to standard test condition (STC) power measurements for monitoring the degradation progression during the environmental stress testing, weak-light measurements were recorded after the different degradation steps for every cell type. For a standard module with crystalline silicon cells the efficiency loss, from 1000W/m^2 to 100W/m^2, is about 5–10% (according to the internal PI-Berlin database 2008–2012); all tested modules also demonstrated this during the initial determination.

> "Efficiency losses at lower irradiations become more significant for higher degradation rates."

After the first PID cycles some cell strings showed little or no drop in efficiency at 1000W/m^2, but the change was apparent at weaker irradiances. The reason for this effect is the decrease in shunt resistance which generally happens initially during PID treatment and which has been documented in the literature [1,9]. Efficiency losses at lower irradiations become more significant for higher degradation rates. Fig. 9 shows two examples – one for a comparatively stable module and one for a PID-prone module.

The effect can also be visualized by electroluminescence (EL) images, since low irradiation corresponds to a lower current. Differences in PID can therefore be much better differentiated by EL images

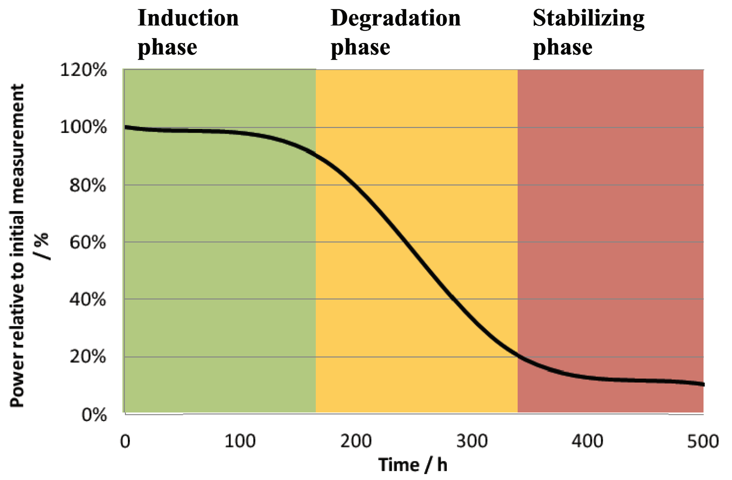


Figure 11. Typical PID degradation progression, consisting of induction, degradation and stabilizing phases.

generated with lower (injection) currents, showing PID-affected cells at an earlier stage, than by images generated with higher currents [10,11].

Acceleration factors between the different test methods

One approach for assessing PID results and which is relevant to lifetime estimations for realistic environments is the determination of activation energies and acceleration factors. A study on leakage currents during PID stress tests and their relation to degradation was recently published [12], and the activation energy of the acceleration factors under various test conditions was investigated. In the studies at PI-Berlin, however, it was found that the relation between leakage current and actual level of degradation is not always straightforward: the relation between high leakage currents and PID-prone module concepts seems to be mainly driven by the encapsulation material. As seen in Fig. 10, the levels of leakage current of three different modules lie in the same range, although the degradation of the modules varies significantly.

All modules showed a nonlinear degradation progression during PI-Berlin's investigations. The degradation phase can be divided into three parts: in sequence, an induction phase (where the module can even demonstrate a slight increase in power), a degradation phase (where the module shows an almost linear degradation progression) and a stabilizing phase (where the degradation process stabilizes at a level which depends on the applied voltage [13]).

To determine the activation energy, a degradation percentage power drop over time was implemented and calculated with the generally valid Arrhenius equation:

$$k_1 = A \times e^{\frac{-E_A}{R \times T_1}} \tag{1}$$

$$E_A = -\frac{\ln k_2}{k_1} \times R \times \left(\frac{1}{T_2} - \frac{1}{T_1}\right)^{-1} \tag{2}$$

where k_1 and k_2 are the degradation rates, R is the Boltzmann constant, T_1 and T_2 are the temperatures and A is the pre-exponential factor.

The activation energies for several modules during induction, degradation and stabilizing phases were determined for 85°C and 60°C and are given in Table 1. To calculate the acceleration factors, the time of treatment from those modules whose power levels were located within the degradation phase were compared for climatic conditions of 85°C/85% RH and 60°C/85% RH. From these results, it is possible to make the following statements:

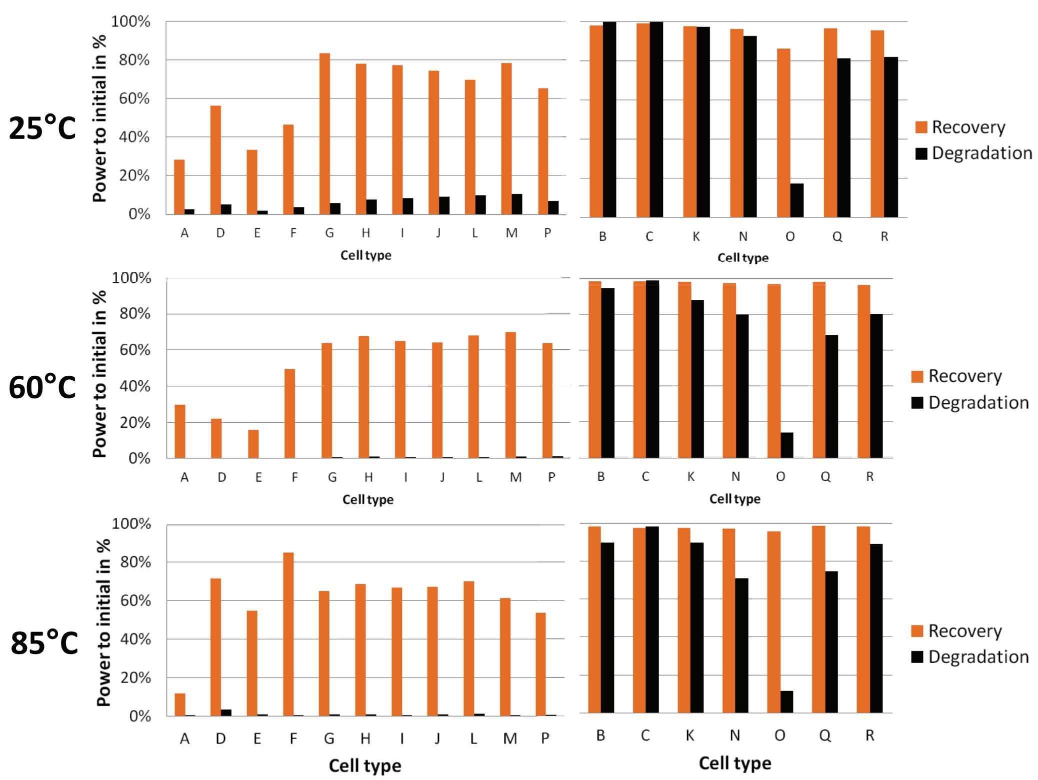


Figure 12. Comparison between PID degradation and PID regeneration of different cell types (A–R) for different climatic conditions, divided into two groups – one with power less than 15% of the initial power (left), and one with power greater than 15% (right).

	Degradation phase		
	Induction	Degradation	Stabilizing
Average activation energy E_A for 85°C and 60°C [kJ/mol]	70.8	54.7	56.1

Table 1. Activation energies for different test methods.

	Below 15% degradation		Above 15% degradation	
Test method	Module power after degradation	Module power after recovery	Module power after degradation	Module power after recovery
25°C	6.45%	63.0%	81.6%	95.7%
60°C	0.68%	52.7%	74.8%	98.1%
85°C	0.95%	61.5%	74.8%	97.5%

Table 2. Average PID level for two groups (degradation level below and above 15%) compared with the average recovery level for three different test methods.

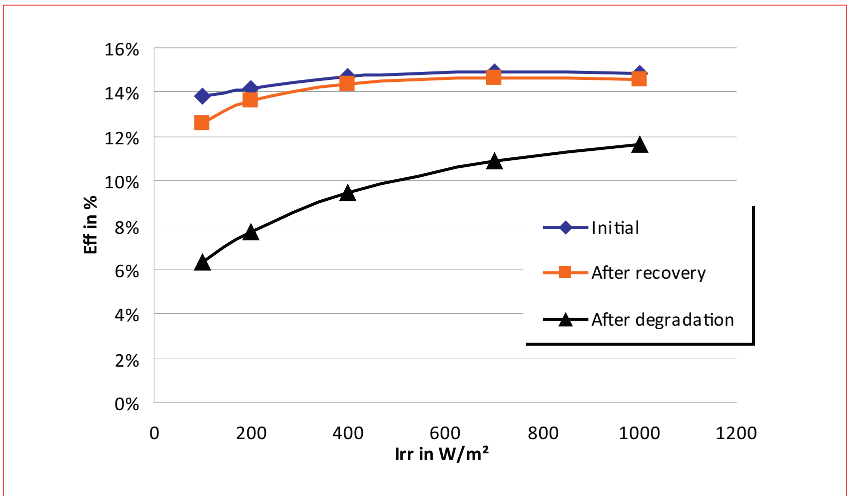


Figure 13. Weak-light performance after different stages of PID.

1. The climatic conditions of 85°C and 85% RH show the most pronounced degradation.
2. Quadrupling the time during climatic conditions of 60°C and 85% RH, which are currently proposed for the IEC 62804 standard, results in the same power degradation.

Regeneration of PID-affected modules

The regeneration of PID-affected modules is an important topic, especially for modules which have been out in the field. The question is, can modules with PID be regenerated by a reverse potential, and are there any differences between the modules stressed by various climatic conditions?

To address these topics, the modules which were degraded by different test cycles in the first run were recovered at the same conditions for the same period of time. STC power measurements and EL images were subsequently taken to compare the samples. In the end, the modules could be divided into two groups: modules with a power greater than 15% of the initial value after degradation, and modules with a power less than 15%. As can be seen in Fig. 12, all modules with a residual power above 15% could be recovered to an average of 97% of their initial values. Modules with a higher power loss could only be recovered to an average value of 59%.

> "All modules with a residual power above 15% could be recovered to an average of 97% of their initial values."

Table 2 shows that the difference in the final degree of recovery between the different test conditions is rather small and mostly driven by the average degradation at the beginning of the recovery process. Almost all of the modules could not be recovered to their initial power. It became particularly clear that high degradation levels of modules corresponded to significantly lower recovery levels.

Apart from recovering STC power, another aspect of PID recovery is recovering the shunt resistance, which affects the weak-light performance of modules (see Fig. 13). Even in the case of a more or less full recovery of STC performance, there might be still a reduction in weak-light performance.

Summary

The main topic of this article has been the impact of the ARC on the PID effect – the significant influence of different ARCs on the PID stability of a cell/module was demonstrated. Investigations of multi-layer structures were motivated by the known dependency of the PID effect on the refractive index. The implementation of double- and triple-layer ARC structures was found to reduce, but not completely prevent, PID.

> "The implementation of double- and triple-layer ARC structures was found to reduce, but not completely prevent, PID."

Alternative approaches for modifying the ARC by varying certain process parameters for deposition (such as deposition rate, temperature and gas composition) in order to reduce the PID effect were considerably more effective. Furthermore, it was shown that PID-affected cells potentially cause a higher risk of hot spots than unaffected cells, and that PID can have a significant effect on weak-light performance.

Relevant PID test conditions were also compared: an increase in the rate of degradation by a factor of four was determined for 85°C/85% RH conditions relative to 60°C/85% RH. Activation energies were determined and found to lie within the range 56.1 to 70.8kJ/mol for different modules; these are comparable to activation energies determined by other authors [12,14,15].

Finally, during investigations of the recovery behaviour of PID-affected modules, it was demonstrated that modules with a degradation level above 15% can be recovered to a minimum level of 96%. Modules with residual powers less than 15% could be recovered to a level of at least 53%. It was observed that PID is not always fully recoverable and that the extent to which this is possible is highly dependent on the initial degradation level.

Acknowledgements

The authors thank centrotherm photovoltaics AG for useful discussions and for providing the cells for the experiments. This work was financially supported by the German Federal Ministry of Education and Research (BMBF) under Contract Number 13N10445 ('FutureFab').

PV Modules

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Simon Koch joined PI-Berlin in 2007. He studied environmental engineering at the University of Applied Science in Berlin, Germany, and received his diploma degree in 2008. For his diploma thesis Simon worked on defect analysis of silicon solar modules using electroluminescence and photoluminescence imaging, and is now focusing on PID simulation for his Ph.D. thesis.

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Defect detection in photovoltaic modules using electroluminescence imaging

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ABSTRACT
Electroluminescence (EL) imaging for photovoltaic applications has been widely discussed over the last few years. This paper presents the results of a thorough evaluation of this technique in regard to defect detection in photovoltaic modules, as well as for quality assessment. The ability of an EL system to detect failures and deficiencies in both crystalline Si and thin-film PV modules (CdTe and CIGS) is thoroughly analyzed, and a comprehensive catalogue of defects is established. For crystalline silicon devices, cell breakages resulting from micro-cracks were shown to pose the main problem and to significantly affect the module performance. A linear correlation between the size of the breakages and the power drop in the module was established. Moreover, mechanical stress and temperature change were identified as the major causes of the proliferation of cracks and breakages. For thin-film modules, EL imaging proved the existence of an impressive reduction in the size of localized shunts under the effect of light-soaking (together with a performance improvement of up to 8%). Aside from that, the system voltage was applied in order to monitor transparent conductive oxide (TCO) corrosion effects and laser-scribing-induced failures, as well as several problems related to the module junction box in respect of its sealing and the quality of its electric connectors.

Introduction
Photovoltaic cells are optimized for absorbing light and converting it into electricity. Because of the reciprocity principle, they can also be stimulated to emit photons, thereby offering a basis for optical characterization techniques. In recent years, a variety of optical tools, which in part had been developed for other applications, have been investigated for quality assessment in the photovoltaic industry. Electroluminescence (EL), photoluminescence (PL), laser-beam-induced current imaging (LBIC) and thermal imaging are examples of the best-known techniques.

“EL has been recently integrated as an investigative procedure for photovoltaic devices.”

An optical technique which has been used for many years [1] in lighting applications, EL has been recently integrated as an investigative procedure for photovoltaic devices. It consists of applying a direct current to the module and measuring the photoemission by means of a camera sensitive to near-infrared. The brightness distribution on the imaged crystalline silicon solar modules correlates with the distribution of the open-circuit voltage V_{oc}, the minority carrier diffusion length and the series resistance, as well as with the quantum efficiency and the ideality factor of the examined cell [2–5]. The work at hand focuses on presenting the measurement set-up for EL imaging and evaluating its capabilities regarding quality assessment and defect detection in solar cells and modules of different technologies.

EL measurement system

Equipment
For this investigation, a back-illuminated Si-CCD camera from Great Eyes with a high near-infrared (NIR) sensitivity (quantum yield 85% @ 750nm, 40% @ 900nm and 10% @ 1000nm) was used. The system features a resolution of 1024 × 1024 pixels and a pixel size of 13µm × 13µm. The dynamic range of the recorded data amounts to 16 bits. The camera is equipped with a Minolta MD W.Rokkor Objective with a focal length of 35mm and a maximum F-number of f/1.8. The system is mounted on a freely adjustable tripod inside a black tunnel, allowing both close-up measurements of different module sections (with a minimum camera–object distance of 30cm) and overall shots of complete modules. The 5.5m tunnel length is suitable for full-size images of all common panel sizes up to 2m × 2m.

The power supply is ensured by a TDK-Lambda GEN300-11 programmable DC unit with a maximum voltage output of 300V and a maximum current output of 11A. The integrated synchronization module allows control of the EL camera as well as communication with the measurement software. The user–system interaction is based on the LumiSolar Mobile software. In general, the power supply should be chosen in such a way that the maximum applicable voltage and current are at least 120% of the respective values of open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) of the module under test.

The system validation was performed, through a qualitative and quantitative comparison of EL measurements of two reference modules, by the system at GE Global and by an electroluminescence set-up at the Fraunhofer ISE research centre in Freiburg.

System parameter optimization

Aperture size and exposure time
Images can only be sharpened to the extent that the quality of the focal lens and of the photo detector allows. A smaller aperture size improves the sharpness of an image and makes it less sensitive to optical aberrations. However, this comes at the cost of a lower light exposure, thus resulting in lower counts, which can only be compensated by a higher exposure time. The consequent risk is that different areas might exhibit, over a period of time, a changing behaviour in photoemissions, due to heating. The linearity of the EL signal was therefore analyzed within different areas of the module and is shown in Fig. 1.

The averages of the pixel grey values were calculated (i) for the whole module – blue diamonds in Fig. 1(b); (ii) for a rectangle including a shunted cell – red inset in Fig. 1(a) and red squares in Fig. 1(b); and (iii) for a small rectangle of 2 pixels × 5 pixels at the bright spot of a shunt – orange rectangle in Fig. 1(a) and orange circles in Fig. 1(b). As can be seen from the linear fits (red lines in Fig. 1(b)), the EL signal increases linearly with the integration time for all three selections

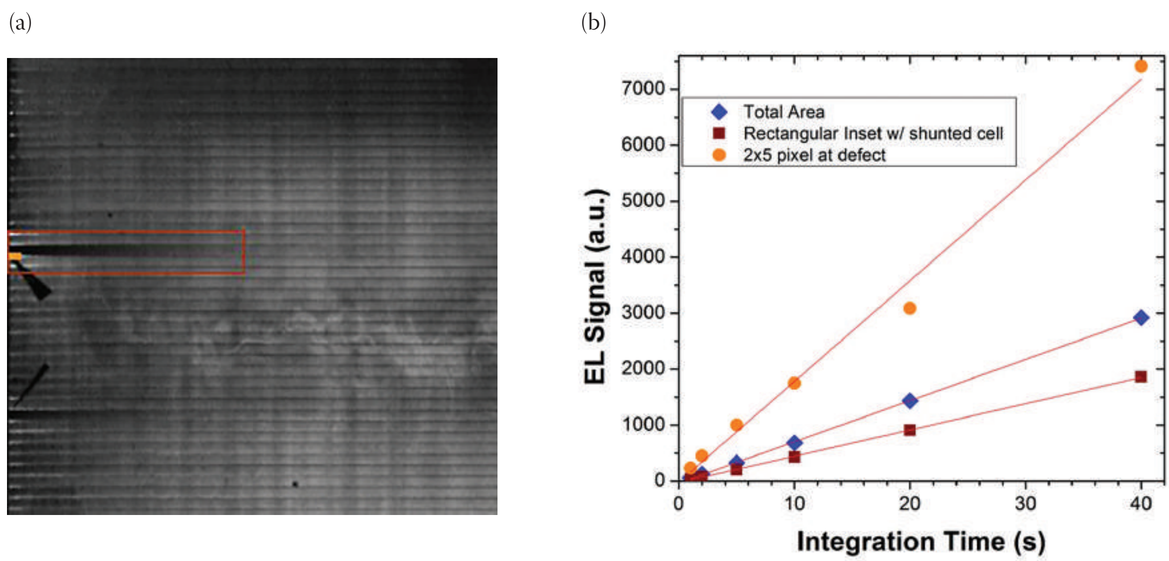

Figure 1. (a) Section of a CdTe module with the analyzed areas indicated. (b) EL signal intensity at different integration times for different areas of the CdTe module.

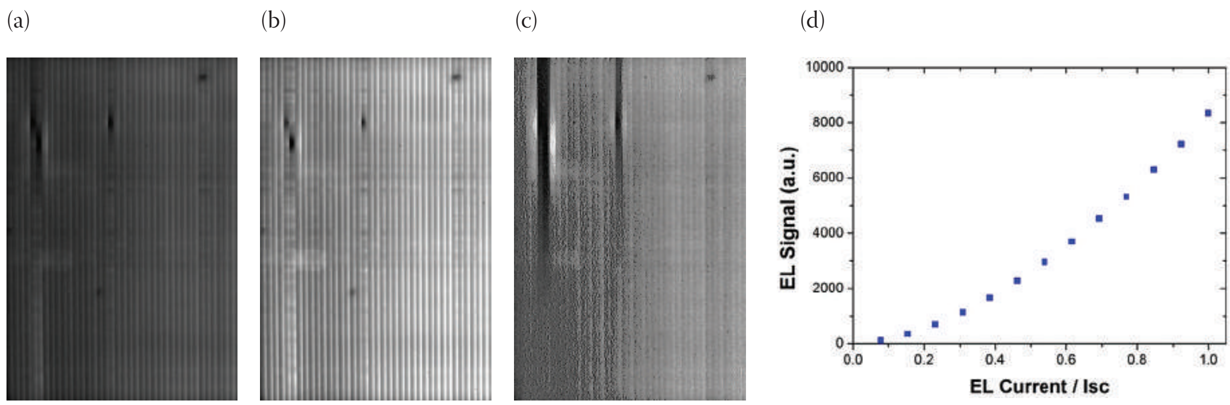

Figure 2. Influence of current on EL signal strength, taken at (a) $0.5\times I_{sc}$ and 60s; (b) $1.0\times I_{sc}$ and 60s; and (c) $0.15\times I_{sc}$ and 60s (brightness up-scaled 15×). (d) Mean grey value over different currents.

(R^2 > 0.99 for all data sets). Hence it is concluded that, with integration times of 40s and currents close to the I_{sc} of the module, non-linearity effects caused by module heating are negligible. In general, an integration time of 10–30s at excitation currents close to I_{sc} was sufficient to achieve a high image quality and a good signal-to-noise ratio.

"Comparing El images with different currents allows different types of defects to be identified."

Operating voltage and current

The purpose of applying an electric voltage during the EL imaging is to counter the electric field in the depletion zone, thus allowing the charge carriers to diffuse into the p-n junction and to recombine radiatively. The diffusion process, and thus the current, increases almost instantly when the applied voltage reaches the V_{oc} level. In order to prevent the power supply from damaging the module, it is recommended to operate the excitation power supply in constant current mode. The excitation current should also not exceed 120% of the device's I_{sc}. Comparing El images with different currents allows different types of defects to be identified, as shown in Fig. 2. Shunted cells can be easily recognized, as their area of influence (the screening length of a shunt) decreases with a higher current. Images with a very low applied bias can be very useful for

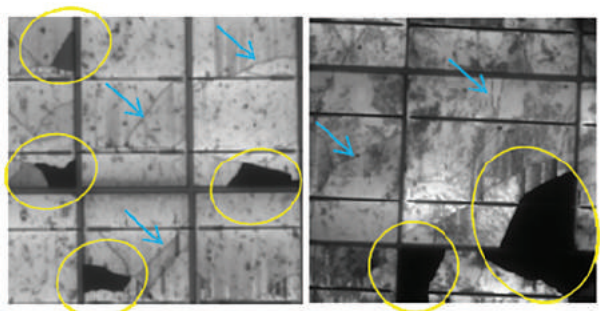

Figure 3. Cracks and breakages in crystalline silicon cells.

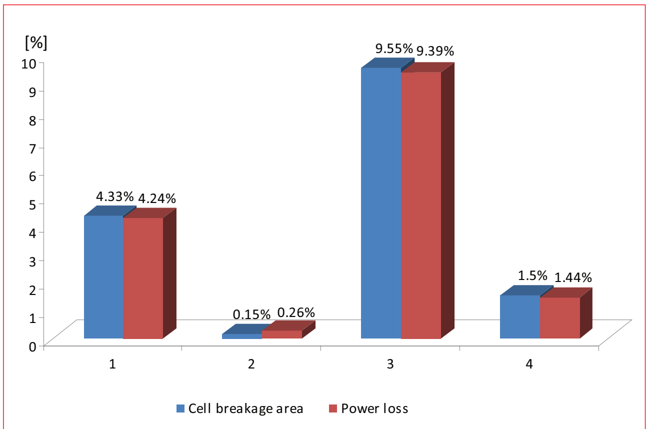

Figure 4. Correlation between cell breakage area and power loss.

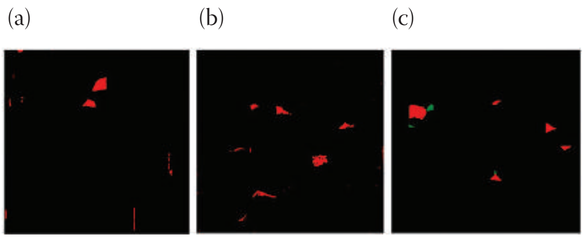

Figure 5. Propagation of cell cracks and breakages in a c-Si module under different stress conditions: (a) mechanical load test; (b) hail test; and (c) thermal cycling.

visualizing the effect of diode shunts, but a lot of the contrast and spatial resolution of the defects is lost. Differential images of the same module at different currents are probably the best for revealing these phenomena.

Defects in crystalline silicon modules

Cracks and breakages

Cracks and breakages in the semiconductor material are responsible for the majority of cases of power loss in crystalline silicon cells. Cracks generally impact only a small line and hence do not severely affect the output power [6]. However, they can also damage the contact fingers, resulting in the development of cell breakages, especially if the crack propagates in a direction perpendicular to the fingers. Fig. 3 shows the typical appearance of cell cracks (blue arrows) and breakages (yellow circles) in crystalline silicon cells. The contact fingers are aligned vertically in these images.

To accurately assess the impact of cell breakages on device performance, the output power of four modules of different sizes was measured in a flash solar simulator. For each module, an EL measurement was taken, and the breakage areas – appearing dark in the EL image (grey values under a certain threshold) – were integrated. A direct correlation between the total breakage area and the power drop was clearly observed. The comparison results are shown in Fig. 4.

In the search for the reasons behind the occurrence and propagation of cell cracks and breakages, several crystalline silicon modules were exposed to different stress conditions and the EL measurements before and after the experiment were compared. All pixels featuring a grey value over a certain threshold and corresponding to the newly formed cracks and breakages are marked in red on the resulting images of the stress tests (Fig. 5).

The application of a mechanical load of approximately 4500Pa to a polycrystalline silicon module (front and rear side) for a duration of two hours induced the occurrence of several new cracks as well as the

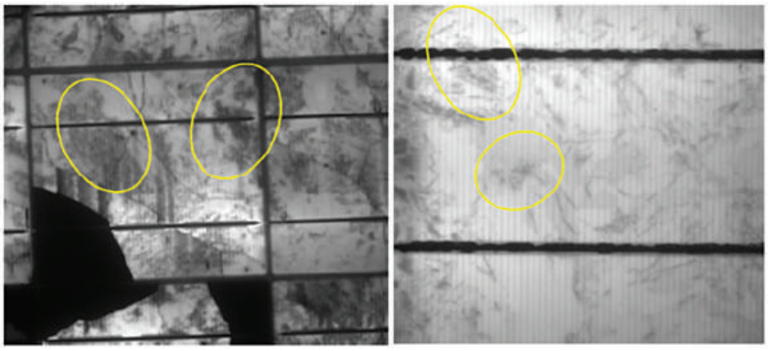

Figure 6. Crystal inhomogeneities in crystalline silicon cells.

development of a number of cell breakages, generally situated between two pre-existing cracks (Fig. 5(a)). Similar effects could be noticed under the influence of punctual, short-term strains, such as the impact of hailstones (simulated using a hail cannon and ice balls according to the endurance-test norm). The corresponding differential image is given in Fig. 5(b). On the other hand, temperature cycling experiments did not show conclusive degradation effects: several modules were exposed to five temperature cycles with a 10-hour period, varying between –40°C and +85°C in the climate chamber. Some cracks and breakages appeared (Fig. 5(c): red areas), but other areas with existing defects regained their activity (Fig. 5(c): green areas). This effect can be explained by the expansion and contraction of the metallic contact fingers through temperature modulation. Depending on their position and depth, contact interruptions due to cell cracks can be restored or extended.

Crystal inhomogeneity

A further imperfection of crystalline silicon cells, which can be easily detected using EL imaging, is crystal inhomogeneity; this appears in the EL image as distributed dark areas with a granular appearance (Fig. 6). These inhomogeneities can have various causes [7], such as process-related fluctuations in dopant concentration or in material thickness, and inherent non-uniformities related to structural defects and to the quality of the material itself.

Defective edge isolation

Short circuits may appear during the edge isolation process. The electric potential difference between the n-doped and p-doped semiconductors of the p-n junction decreases, leading to a weaker detectable EL signal in the measured data. Fig. 7 shows a section of a polycrystalline silicon module with defects in the isolation of the cell edges.

Contact grid interruptions

Flaws in the cell production process can lead to local interruptions/failures of the contact fingers before or during the contacting operation. Depending on the position and width of the contact gap, the impact of this defect on the module power output can vary greatly. Contact finger interruptions situated on the cell edges pose a particular problem: in the outer fingers of the solar cell, the current is injected by a single busbar, so the finger interruption causes a complete contact outage between the finger gap and the cell edge. In the EL image, these defects are easily detectable in the form of dark areas surrounding the interrupted finger and reaching to the cell edges (blue arrows in Fig. 8).

> “Shunts and weak diodes have a very particular EL brightness pattern.”

Defects in thin-film modules

Shunts and weak diodes in light-soaking studies

Shunts and weak diodes are localized between the front and the rear contacts of the solar cell. They result in a lower open-circuit voltage and thus a lower fill factor of the cell. Several mechanisms can be behind the occurrence of shunts and weak diodes, including failures in the deposition procedure (resulting in a discontinued or a locally too-thin p-type semiconductor layer), faulty laser scribing (inducing p n junction damage), and the presence of dust particles or metal traces. Shunts and weak diodes have a very particular EL brightness pattern: a localized darkness within a single cell, having a particularly dark centre and a symmetric appearance along the cell. The screening length of shunts and diodes also increases with decreasing excitation current. In the scope of this work, shunts and weak diodes were barely noticeable in crystalline Si modules but are very common in thin-film devices, especially those based on CIGS.

During the investigation of local shunts and weak diodes, it was proved that light-soaking treatment reduces their size considerably and thus their impact on module performance. EL images of a CIGS module after a long-term dark storage are presented in Figs. 9(a) and (b); the corresponding images after the module was treated for 24 hours in the light-soaking station under $1000 \cdot W/m^2$ are given in Figs. 9(c) and (d). The difference between before and after the light-soaking process is remarkable: a significant reduction in the size of the dark areas surrounding the spots with shunts/weak diodes as well as an increase in operating voltage (+6.3%) and module output power (+8%). Other studies have explained the rise in operating voltage by the light-soaking-induced rise in the charge-carrier density [8,9]. Evidence was found that a reduction in shunts and weak diodes also plays a role here, and further studies are necessary to fully explain the light-soaking enhancement in CIGS solar cells and modules.

Potential-induced degradation (PID)

The corrosion of the transparent conductive oxide (TCO) layer is known to mainly affect modules based on glass substrates when exposed to high negative voltages at high temperatures and humidity levels [10,11]. The corroded front contact interrupts the charge-carrier transport into the junction, and the affected areas appear dark in the EL image.

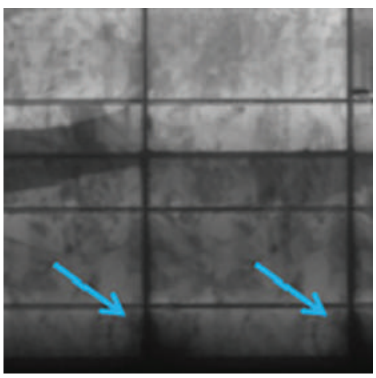

Figure 7. Defective edge isolation.

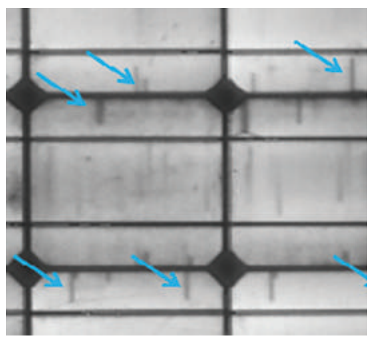

Figure 8. Contact finger interruptions in a monocrystalline silicon cell.

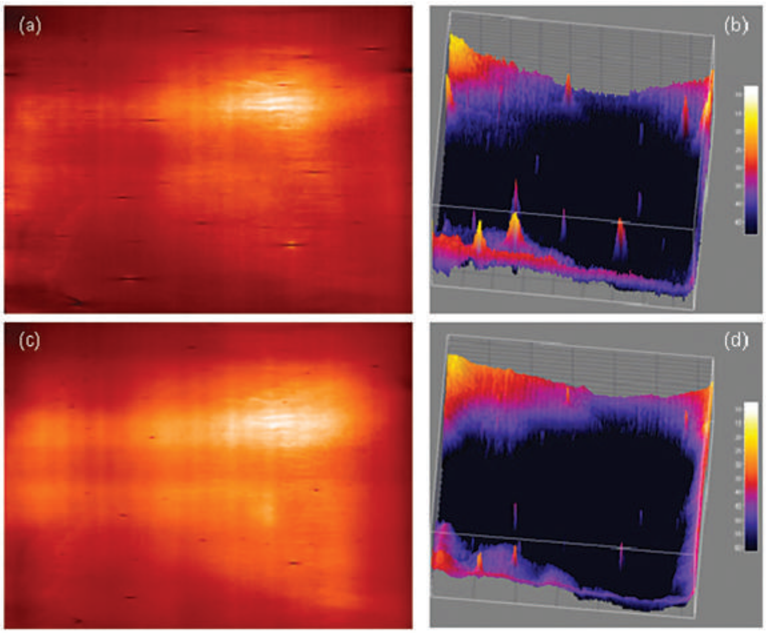

Figure 9. Development of shunts and weak diodes in CIGS-based modules: (a,b) before light-soaking; (c,d) after light-soaking. The colours in images (b) and (d) are inverted for better visualization of defects.

To investigate the correlation between the changes to EL images through PID and the power drop in thin-film panels, a negative potential of 1kV was applied to the shunted contacts of a CdTe-based module while the glass surface was grounded by gluing to it an aluminium foil that was connected to the ground of the high-voltage source. The module was exposed to 85°C and 85% relative humidity for 250 hours in a climate chamber. Power and EL measurements were taken before and after the test, as well as at intermediate stages. A dependency between the dark area and the power drop can be seen in Fig. 10. EL allows the identification of the weak points of the module: in this case it is the edge sealing, which allowed moisture penetration, enhancing TCO corrosion. The dark areas are at the edges, whereas no degradation is visible at the junction box. The dark areas do not change in size when different excitation currents are applied and, hence, are not related to shunts and weak diodes but rather to contact layer degradation. It is assumed that TCO corrosion is the major source of degradation observed here.

Laser-scribing failures

Failures can occur during the laser-scribing process for monolithic cell interconnection in thin-film modules. Three scribes are necessary for creating the cell interconnections, as shown in Fig. 11(a). P1 and P3 separate adjacent cells by interrupting the front (P1) and back (P3) contact layers. The purpose of P2 is to provide the connection between the front and back contacts of two neighbouring cells. An interrupted scribing line can result in a shunting bridge over P1 (Fig. 11(b)) or P3 (Fig. 11(c)) in cell A or cell B respectively, and no EL signal is visible close to the bridge.

Fig. 12 shows an example of a module with two different scribing-line bridges (red arrows).

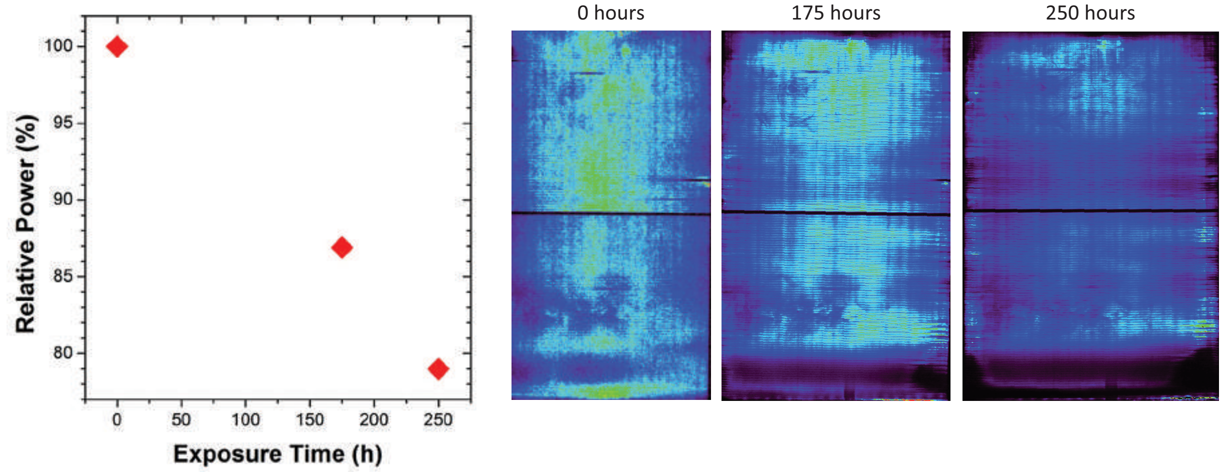

Figure 10. Progression of TCO corrosion in a thin-film CdTe module.

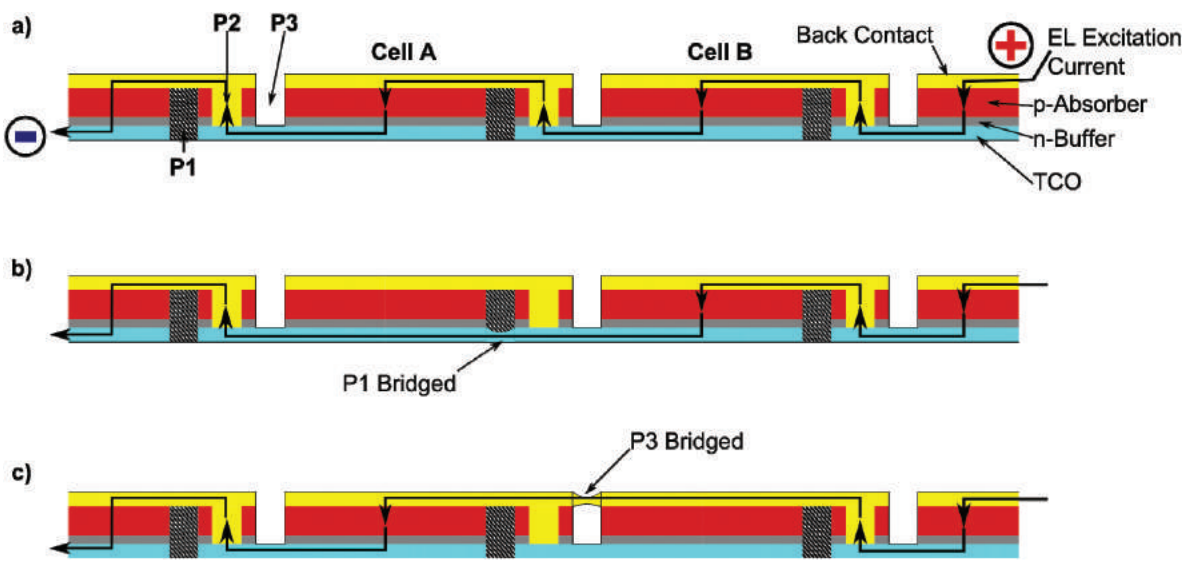

Figure 11. Schematic of the typical monolithic cell interconnection of thin-film modules grown in a superstrate configuration: (a) intact configuration of neighbouring cells; (b) bridged P1 scribe; (c) shunt over the P3 scribe.

"An EL imaging system is capable of accurately detecting numerous failures originating from the cell production process."

Conclusion

This paper has shown that EL imaging represents a powerful quality assessment tool for both crystalline silicon and thin-film solar modules. When properly adjusted and configured, an EL imaging system is capable of accurately detecting numerous failures originating from the cell production process. Furthermore, it is a very useful tool for observing and explaining the changes in cell or module performance that are generated by mechanical, electrical or environmental stress tests.

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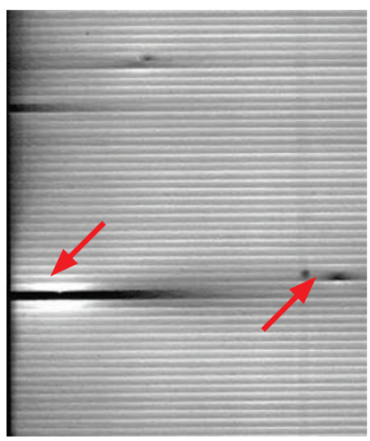

Figure 12. Scribing-line bridges in a CdTe thin-film module (image taken at 650mA and 40s).

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PV Modules

Power Generation

Isofoton proposes largest Latin American project

Product manufacturer Isofoton has signed a US$100 million agreement with the National Electricity Council of Ecuador, CONELEC, to construct a 50MW PV plant in the country.

The solar facility will be in the parish of Calderón, 10 km from Quito, employing 500 people. The plant will have a nominal power rating of 49.6MW and a peak rating of 54.065MWp, making it one of the largest in Latin America both in terms of size and production capacity.

The company said the plant would generate 84.093MW/hour of clean energy, equivalent to the consumption of 84,000 households, reducing CO2 emissions by 49,000 tonnes per year.

Source: Isofoton

The agreement is worth approximately US$100 million withCONELEC to construct a 50MW PV plant in the country.

Europe News Focus

Order Focus: Deger supplies tracking systems for the two "largest PV systems in Bosnia-Herzegovina"

Deger, a manufacturer of solar tracking systems, has supplied 30 DEGERtracker 9000 NT tracking systems for installation at two 150kWp solar parks in Bosnia-Herzegovina.

Contractor GP Toming installed 15 DEGERtracker 9000 NT tracking systems at each of the two plants which are located in Drinovci and Stolac. According to Deger, its tracking systems incorporate a patented Maximum Light Detection (MLD) technology, which enables the systems to achieve on average a 45% higher yield in comparison to rigidly mounted systems.

The company also installed 504 PV modules at each site. Each module has a PV capacity of 295 watts.

Source: Deger

The projects are equipped with Deger's DEGERtracker 9000 NT tracking systems.

European grid project seeks to overcome PV integration challenges

A two-year European Commission-funded project has been launched to investigate ways of integrating more PV electricity into the European grid.

The so-called PV Grid project is being led by a consortium of 20 members — consisting of national PV associations, distribution system operators, universities and consultants — and will examine the practical challenges preventing greater grid integration of PV in Europe.

The project is being funded by the European Commission's Intelligent Energy for Europe programme and will run until October 2014.

Nanosolar completes 10.63MW installation

CIGS solar panel company Nanosolar completed a 10.63MW solar project in Alfarrasi, Spain, the company's largest installation to date.

Located in Spain's Valencia region, the solar project was developed by Smartenergy Invest and Advanta Capital.

The installation, which was connected earlier this month, is said to be the region's largest PV power plant to date. It has the ability to generate 16,500MWh of electricity per year using its 50,000 panels that are spread across 26 hectares of former agricultural land.

REC completes 14.8MW PV plants in Germany

REC, a provider of solar services, has completed the installation of two PV power plants in Germany — a 3.8MW PV plant in Schongau and an 11MW PV array in Schependorf.

The company was appointed as EPC contractor and supplied PV modules for both projects. As part of the development process for the 3.8MW plant, REC organized all necessary permits and due diligence and co-ordinated more than 250 construction workers at the plant's site.

The company installed 16,560 REC Peak Energy Series modules at the site which help to produce 4.5 million kWh of output every year. According to REC, its modules ranked first for energy yield in Photon Laboratory's 2011 Module Field Performance Test, producing 6% more energy than the test average.

Government rifts will 'destroy confidence' in UK solar industry

Apparent attempts by senior government figures to dismantle UK renewable energy commitments will prove "disastrous" to solar and other clean technologies, leading industry figures have warned.

Source: Alan Dean

Chancellor George Osborne and other senior UK ministers and MPs are alleged to have been trying to water down legally binding commitments to cut greenhouse gas emissions.

An undercover film released in November by environmental body Greenpeace revealed the apparent extent to which the Chancellor George Osborne and other senior UK ministers and MPs are trying water down legally binding commitments to cut greenhouse gas emissions through investment in low carbon energy generation.

Those implicated in the film have denied its claims.

Helios Strategia installs 2.5MW PV plant in Romania

French PV project developer Helios Strategia has completed a 2.5MW PV plant in Ploiesti, Romania.

Source: Helios Strategia

Helios Strategia has completed a 2.5MW PV plant in Ploiesti, Romania.

Spanning an area of seven hectares, the plant was developed by Helios Strategia in partnership with unnamed local partners and co-investors. It utilises PV modules manufactured by Suntech and inverters supplied by Power One.

Flanders PV installed capacity falls by 69.15%

Solar PV installed capacity in Flanders, Belgium, experienced a 69.15% drop this year since 2011.

According to Flemish energy regulator VREG, Flanders has added 245MW of new PV capacity so far this year, beaten only by biogas which generated 250MW, bringing the region's total installed PV capacity to 1.94GW.

These figures correlate with the decrease in green certificates awarded to consumers from the Flemish electricity board VREG. In 2011, 84.264 certificates were offered, but in 2012 the number fell by over half to 36.594.

Source: REC

REC has completed an 11MW PV plant in Schependorf.

News

GCL Solar completes two solar projects in California

GCL Solar Energy's California PV projects consist of two solar installations totalling 48MW.

The polysilicon and wafer supplier, a subsidiary of GCL-Poly Energy Holdings, developed the projects in Tulare and Kings County, California. An undisclosed buyer will own and operate the projects for a price tag of around US$50.5 million. Power is being sold to Pacific Gas and Electric under a 25-year power purchase agreement.

Blackstone launches solar programme for portfolio companies

US investment firm Blackstone has launched a solar programme which aims to improve the environmental performance of its portfolio of companies and real estate assets.

The programme — which was developed in collaboration with Blackstone's Private Equity, Real Estate and Advisory businesses — has been set up as part of an ongoing effort to focus on sustainability across the firm for companies it manages and advises. According to Blackstone, it has the potential to help its portfolio to reduce energy costs by around 10%.

Lightway Solar America enters supply agreement with Premier Power

Solar panel manufacturer Lightway Solar America and California-based project developer Premier Power Renewable Energy have signed a 16.6MW supply agreement for solar projects that will be built in 2013.

Lightway Solar America, a subsidiary of China's Lightway Green New Energy, will begin shipments during the fourth quarter of 2012. The panels will be used by Premier Power, which also provides engineering, procurement and construction services, for its solar projects in the US and European markets.

Ceremony dedicates Arizona's 19MW Queen Creek project

Officials from PSEG Solar Source, the Salt River Project (SRP) and juwi solar have gathered with local officials and business leaders in Queen Creek, Arizona to dedicate the 25MW(DC) (19MW, AC) solar farm.

Located just outside of Phoenix, the Queen Creek Solar farm uses nearly 90,000 crystalline solar panels, which are mounted on a single axis tracking system, and 48 400kW solar inverters, which each have six 67kW extractable modules with customised configuration.

Owned by PSEG Solar Source, a subsidiary of American company Public Service Enterprise Group (PSEG), the company served as the engineering, procurement and construction manager for the solar farm, which will sell its power to public power utility SRP under a 20-year agreement. Phoenix's Power-One delivered the inverters used for the installation and Colorado's juwi solar served as project developer.

El Paso Electric and Element Power ink PPA for 50MW project

Utility firm El Paso Electric (EPE) has signed a power purchase (PPA) agreement relating to the total output from the proposed 50MW Macho Springs Solar Project, which is due to be constructed near Deming, New Mexico in the US.

Owned by renewable energy developer Element Power, the Macho Springs Solar Project will be built on land leased from the New Mexico State Land Office with construction expected to begin in 2013.

During the construction phase, the project will create an average of 400 jobs. Scheduled to complete in 2014, the PV system is expected to be the "largest solar project in the state of New Mexico". It is also expected to produce enough output to power 18,000 households.

The PPA is subject to approval by the New Mexico Public Regulation Commission.

The hybrid system will generate electricity to power water pumps and a desalination plant in the Egyptian desert.

Asia & Oceania News Focus

Power-One, Phono Solar partner to sell PV systems

Power-One, an inverter manufacturer, and module manufacturer Phono Solar have signed a strategic alliance to market and sell PV systems using their respective technologies.

Power-One will provide its inverters and monitoring platform for the PV systems, which will be sold worldwide. Both companies will rely on their research and development resources for joint product development and work as preferred key equipment suppliers for current and future large scale projects.

Phono Solar's parent company, the Sumec Group, advised that it will provide access to large PV projects in China. The companies said that they will focus on selling the systems in China, Japan, Australia and other Asia Pacific countries with promising, developing, PV markets.

Fonroche agrees 24MW Kazakh project as prelude to 2GW plans

French renewables company Fonroche Energie has agreed a deal to build a 24MW solar plant in Kazakhstan as a forerunner to a possible 2GW project in the country.

The company's Chief Executive Thierry Carcel told *PV-Tech* that the project would trial a number of different PV module and tracking technologies to establish which are most suited to local conditions.

Carcel explained that the project would deploy various technologies, including high and low concentration PV, thin film and multi- and mono-crystalline modules. A variety of tracking technologies will also be trialled.

If the first phase of the project is successful, Carcel said he had a "gentleman's agreement" with the Zhambyl region governor Yernur Dzhienbaev to build up to 2GW of solar.

Construction work on the pilot is due to begin next year.

Africa & the Middle East News Focus

juwi builds off-grid hybrid PV system in Egyptian desert

German renewable energy specialist juwi has constructed its first project in Egypt — an off-grid hybrid system which consists of a 50kW PV array, four small wind turbines and a battery storage unit.

Located in Wadi El Natrun, a valley surrounded by barren desert situated between Cairo and Alexandria, the hybrid system will generate electricity to power several water pumps for irrigation as well as a plant for desalination of groundwater. The battery system, which has a storage capacity of 500kWh, will ensure that the water pumps and desalination plant are able to operate 24 hours a day.

The project uses technical equipment, PV modules and inverters delivered from Wörrstadt, Germany while the four small turbines were delivered from the Netherlands. juwi worked with an Alexandria-based electricity company to build the hybrid system in just two weeks.

Canadian Solar expects 50% of business to come from PV projects

Canadian Solar's CEO expects 50% of its revenue will be generated from its PV power plant project business in the next two years, marking a significant shift in its business model.

Dr. Shawn Qu, Chairman and Chief Executive Officer of Canadian Solar made the claim during prepared remarks in a conference call to discuss Q3 2012 financial results.

The company is following the increasing trend of major PV manufacturers such as First Solar and SunPower in becoming increasingly reliant on project business to generate revenue but, importantly, at higher margins than simply selling modules, due to severe price declines and diminished margins.

Canadian Solar said gross margins were 2.2% in Q3, down from 12.4% in Q2 2012, yet would be in the range of 1-3% in Q4.

Canadian Solar's CEO expects 50% of its revenue will be generated from its PV power plant project business in the next two years, marking a significant shift in its business model.

Tariff boosts solar shipments in Japan

The domestic shipment of solar cells and modules in Japan rose 80% in the July-September quarter of this year, following the introduction of a feed-in tariff in the country.

Domestic shipments rose to 627MW from 348MW in the same quarter last year, according to the Japan Photovoltaic Energy Association.

Imports to Japan of PV modules tripled to 203MW, while exports fell to 153MW, down by 57%, the association said.

Product Reviews

Atonometrics

Atonometrics offers reduced uncertainty in irradiance measurements of PV power plants

Product Outline: Atonometrics, a developer of PV test and measurement technologies, has developed a new suite of product offerings, which include the Irradiance Measurement System, the PV Module Soiling Measurement System and the PV Module Degradation Measurement System. By quantifying the effects of various elements on PV power plant performance, the tools allow operators to mitigate risk and maximize return on investment.

Problem: As wary lenders look to safeguard solar investments with high-demand performance guarantees, a clear need has emerged for more accurate PV performance measurement at a project site. Using side-by-side module comparisons, PV power plant operators can demonstrate the real-world effects of factors like soiling and potential induced degradation to ensure long-term bankability.

Solution: Atonometrics recently completed a study demonstrating the ability of a PV reference device (PVRD) to reduce uncertainty in irradiance measurements to just ±2.4 per cent, versus ±5.2 per cent for other technologies. Module soiling is also another issue, causing monthly power loss rates of more than 10%, in turn reducing a project's return on investment. The Atonometrics Irradiance Measurement System is designed to transform a cell or module planned for use at a project site into a PV reference device to measure insolation.

Applications: Commercial and utility-scale PV power plants, including most types of module technology.

Platform: Unlike current technologies, such as pyranometers, Atonometrics' solution enables automatic compensation for changes such as seasonal effects, angle of incidence, spectral content and ratio of direct to diffuse radiation.

Availability: September 2012 onwards.

QBotix

QBotix uses intelligent robots to offer low-cost module tracking system

Product Outline: Start-up QBotix has revealed the 'QBotix Tracking System' (QTS), a dual-axis tracking system that employs rugged, intelligent and mobile robots to dynamically operate solar power plants and maximize energy output.

Problem: Solar tracking systems increase energy production by aiming solar modules towards the sun and tracking the sun as its relative position moves during the course of the day. Conventional tracking systems are claimed by the company to be expensive, unreliable and complex to install and maintain.

Solution: QTS provides the higher performance and energy output of dual-axis tracking at conventional single-axis tracking prices. QTS increases the energy production of ground-mounted solar power plants by up to 40% over existing fixed mount systems and lowers the levelized cost of electricity (LCOE) by up to 20%. In addition, QTS offers fast installation, has low operations and maintenance costs and is compatible with all solar panels and mounting foundations. This results in a better return on investment for project developers and investors, greater system reliability and performance for operators and owners, and solar energy that competes in price globally with conventional grid power for utilities and consumers.

Applications: QTS is compatible with all standard solar modules, inverters and foundation types used in ground-mounted installations.

Platform: QTS utilizes a pair of autonomous robots, one primary and one back-up, to control 300kW of solar panels, which are installed on QBotix-designed mounting systems that do not have any individual motors, while being optimized for cost, strength, durability and installation simplicity.

Availability: QTS is now available for commercial deployments.

Suntech

Suntech's 72-cell module comes in compact configuration for low LCOE

Product Outline: Suntech is introducing a new generation of its large-sized 72-cell module for commercial and utility-scale electricity generation in Europe and the USA. The SuperPoly STP305-24/Ve comes with 15.7% module efficiencies.

Problem: Because of ongoing declines in feed-in tariffs and the elimination of incentives for utility-scale projects in many European countries, continued attention in offering the lowest levelized cost of energy (LCOE) is required for PV projects.

Solution: Suntech's SuperPoly technology achieves higher efficiency ratings by utilizing 'quasi-mono' wafer-based solar cells (square wafers and better temperature performance). With 72 six-inch cells, the new 1956x992x40mm module boasts one of the highest fill factors in the industry and lowers project installation costs, offering lower claimed LCOE. In addition, the new Ve-Series modules feature a slim frame design, lowering storage and shipment costs by up to 16%.

Applications: Commercial and large-scale PV projects.

Platform: An improved design reduces frame thickness from 50mm to 40mm, providing a 1.2kg reduction in total module weight, without compromising module stability or durability. The module is certified to withstand extreme wind (3,800 pascal) and snow (5,400 pascal) loads. This superior frame design not only facilitates efficient module handling and installation, but also allows more modules to be installed on rooftops with tight weight constraint, highly relevant for many industrial projects. The new product line also features Suntech's industry-leading 25-year power output warranty, with positive power tolerance, and a workmanship warranty of 10 years.

Availability: November 2012 onwards.

Product Reviews

Bentek Solar

Bentek Solar's PV 101 MDSS handles safety and code compliance under multiple power sources

Product Outline: Bentek Solar has claimed to have developed and introduced the PV 101 MDSS as a cost-effective Multiple Disconnect Safety System (MDSS), which is designed to provide safety and code compliance for PV installations in the USA under National Electrical Code 2011 rules.

Problem: Multiple sources of power are much less common in AC applications. As a result, PV installations contain hazards that many electricians and maintenance personnel are not accustomed to.

Solution: The MDSS contains a bank of load-break disconnects in a compact, free-standing cabinet. Typically, the MDSS is installed next to the inverter and provides the safety and arc flash reduction that is needed in all PV systems, solving a critical safety issue that is commonly overlooked. The MDSS provides code-compliant fuse isolation that inverters do not. This allows fuses in the inverter to be removed safely.

Applications: Commercial and utility-scale PV power plants.

Platform: Bentek Solar's MDSS with optional zone current monitoring is optimized to work with most inverters at both 600 and 1000VDC. The number of inputs and ampacity of the load-break disconnects in the MDSS are matched to the number and ampacity of the internal inverter fuses. This ensures that when the MDSS arrives at the project site, it is simple to install by eliminating the extra racking, conduit and expensive labour that is required with traditional individual knife blade disconnects, saving up to a claimed 30% in total cost.

Availability: October 2012 onwards for the US market.

Dunkermotor

Dunkermotor's new 'Bifurcated Wormetary' gearmotors provide reliable operation of CSP and PTC power plants

Product Outline: Dunkermotor, now part of Ametek Precision Motion Control, has further refined its unique Wormetary gearing to provide dual high-torque outputs from a single, efficient gearmotor. In the field of concentrated solar power (CSP), parabolic trough collector (PTC) technology is one of the most widely used, and Dunkermotor's new Bifurcated Wormetary gearmotors are designed to meet that application's requirements, while offering several unique benefits.

Problem: Both CSP and PTC power plants require highly accurate and reliable tracking systems. Low energy consumption and flexibility in operating speed are required to provide efficient and effective tracking.

Solution: The motor itself is a special long-life brush motor design with 60 volt input and rated for 28.5 N-cm (40.4 oz-in) continuous torque. It features IP65 environmental protection along with a unique condensation prevention membrane to further prolong life. For the CSP application, the Wormetary gearing is non-backdrivable, which is a benefit in the presence of wind loading. With planetary gearing in its output stages, the load is spread over many contact points around each gear, thus offering much greater protection from shock loading than helical gears used in other high-efficiency right-angle gearmotors.

Applications: Wormetary gearing benefits for PTC and CSP power plants.

Platform: The Bifurcated Wormetary gearing combines a right-angle worm gear to turn the corner with a pair of efficient planetary gearboxes for a total reduction ratio of 529:1, without an undue sacrifice in efficiency.

Availability: **August 2012 onwards.**

Kipp & Zonen

Kipp & Zonen updates SHP1 smart pyrheliometer to measure DNI

Product Outline: Following the success of the SMP series of smart pyranometers released last year, Kipp & Zonen is continuing to develop smart instruments with the launch of its SHP1 smart pyrheliometer, designed for measuring direct normal irradiance (DNI) from the sun, which is essential for concentrating mirror or lens-based CSP systems.

Problem: Improved accuracy in measuring DNI provides the opportunity to maximize yield and return on investment.

Solution: SHP1 is based on the well-known CHP 1 model but features digital signal processing, additional interfaces, faster response and improved temperature specifications. SHP1 has an amplified analogue signal output and digital RS-485 interface with 'Modbus' protocol, making it the most versatile pyrheliometer to integrate into system networks. All SHP1 pyrheliometers have the same calibrated output range, which makes it easy to exchange instruments in the field. In addition to the radiation value in W/m2, it is possible to obtain temperature, power supply voltage and other information over the serial bus. With the SHP1, Kipp & Zonen adds smart measurement of DNI, to the smart measurements of global horizontal irradiance and diffuse horizontal irradiance.

Applications: DNI is an essential input for power plants based on concentrating mirror or lens systems.

Platform: All Kipp & Zonen smart radiometers are individually addressable and can be linked together in a multi-drop configuration to a single RS-485 cable that can be hundreds of metres in length. This makes installation easier and saves on cable costs.

Availability: August 2012 onwards.

Power-One

Power-One's AURORA ULTRA inverter offers higher ROI via energy harvest maximization

Product Outline: Power-One has introduced the AURORA ULTRA-700/1100/1500-TL inverter series, which is available in 780kW, 1.17MW and 1.560MW models, making them the largest PV inverter series available in the market. This liquid-cooled inverter gives high power for the minimum footprint, according to the company.

Problem: Power-One has looked beyond optimized inverter cost and developed inverter features to maximize energy harvest and lower BOS costs for multi MW projects.

Solution: Power-One claims to have focused on maximizing the ROI for PV utility plant owners from the product concept phase through to maximizing energy harvesting, lowering the total plant investment and maintenance costs. The ULTRA extends the power range of its inverters to 1.56MW, while maintaining a maximum of 98.6% efficiency and up to four independent MPPT's input channels that offer improved flexibility and energy-harvesting capabilities. In addition to high energy harvesting, the solar power generation loss in the event of an inverter failure is reduced to 390kW, the power level of one inverter building block. The inverter's modular design allows a 390kW block to be field-replaceable. The ULTRA 700/1100/1500 inverters host advanced communication and grid management capabilities.

Applications: Utility-scale PV power plants.

Platform: Built with a NEMA 4X cabinet, the ULTRA is able to operate in harsh environmental conditions. The inverter is available in pre-configured turnkey solutions, including the mounting pad and MV transformer under the AURORA ULTRA STATION product line, eliminating the cost of engineering.

Availability: October 2012 onwards.

Schneider Electric

Schneider Electric's PV string combiners and disconnects deal with complex installations

Product Outline: Schneider Electric has launched a new line of 600Vdc Square D PV string combiners and disconnects, which are designed for today's technologically advanced, larger sized and complex PV system installations.

Problem: PV string combiner boxes are used to integrate multiple PV strings into one output circuit. With PV installations becoming increasingly large and complex, high-performing custom, durable and safe solutions are critical for today's installers and end users.

Solution: The 600Vdc PV string combiner and disconnect works well with all PV systems owing to the wide range of sizes and capabilities. Key features include durability and protection from the elements: the durable boxes protect the series-strings of PV modules from weather, harsh conditions and over-current. The white, UV-resistant coating is claimed to reduce solar gain by 35%. It has a specially engineered enclosure designed to provide dust-tight and rain-tight protection, meeting or exceeding NEMA 3R, 12, and 4 requirements.

Applications: Commercial and utility-scale PV power plants.

Platform: Square D traditional visual blade switch architecture confirms disconnection, while touch safe IP2 interior shielding protects against accidental contact with live wires. In addition, Seismic Certified 100-400 amp string combiner boxes provide earthquake safety. An optional component is the integrated 2.5 kV surge arrestor to protect PV electronics from lightning strikes.

Availability: The 600Vdc PV string combiner and combo disconnect will be available for purchase through solar distributors, as well as electric wholesale channels.

Growatt

Growatt broadens PV string inverter offering with 'High Frequency' Series

Product Outline: Growatt North America has unveiled a new 'High Frequency Series' of residential solar PV string inverters, and a light commercial 'TL3 Series' string inverter. The HF Series inverters are initially offered in 2.0kW, 2.5kW, and 3.0kW power classes, while the TL3 Series inverters are initially offered in 10kW, 12kW, 18kW, and 20kW power classes.

Problem: Installers are increasingly required to provide excellent energy-harvesting performance and return on investment on a PV installation. In deciding system components, focus is moving away from module requirements towards BOS-related issues such as inverter efficiency in MPP tracking and high product reliability rates.

Solution: The HF Series inverters are initially offered in 2.0kW, 2.5kW, and 3.0kW power classes. These products provide exceptionally wide input voltage range, galvanic isolation and freedom from harmonic distortion. The TL3 Series inverters are initially offered in 10kW through to 20kW power classes. These products are dual-input transformerless 3-phase commercial units with 480VAC output. They feature independent MPP tracking and low start-up voltage for longer production days.

Applications: The HF Series inverters are for residential installations, while the TL3 Series inverters are used for light commercial markets.

Platform: The inverters provide RS-485, Wifi, bluetooth, RF and ZigBee communications protocol options and an advanced lightning protection module and up to 97.5% efficiencies.

Availability: The TL3 and HF models are currently in production, with deliveries of the TL3 commencing later in September, while HF models are currently available.

Project assessment for bankability: Quality assurance from the PV module through system planning to sustainable operational management

Ingo Baumann & **Willi Vaassen**, TÜV Rheinland, Cologne, Germany

ABSTRACT
Economic success in operating PV systems depends essentially on the likelihood of their long-term operation and their delivery of the expected energy yield. These requirements, for which a lifetime of 20–25 years is often assumed, are demanding and cannot be met without preparation. Preconditions are the acceptable quality and long-term stability of the products employed (particularly the PV modules, but also all other components and materials) and the absence of damage to these items during transport and handling. Moreover, PV systems must be professionally planned and properly implemented. This includes considering energy yield assessments not only in the initial estimation of the energy yield, but also in the subsequent planning for concrete implementation. In addition, professional operational management and appropriate maintenance measures will ensure operation with maximum availability. Yield insurance policies can safeguard profitability and render the risks calculable; various models exist for this purpose and these must be carefully tested. It is important that the insurances services also cover the possible insolvency of the responsible system and component suppliers.

Module quality as an important prerequisite of stable system operation

In determining module quality, the testing and certification of crystalline photovoltaic modules as per IEC 61215 (design qualification) and IEC 61730 (safety qualification) commonly and indeed rightly serve as minimum requirements. For thin-film modules, adequate standards are applied. Testing according to these standards concerns, among other things, electrical safety, mechanical suitability and the ageing behaviour of the products as exhibited in climate chambers. The point of these tests is to detect early failure and design faults in the module production or component selection. This procedure is an important quality check, an indication of which is the fact that about every fourth module type fails to pass the lab testing for certification in accordance with the aforementioned standards.

Many individual tests are combined with one another in the testing procedure. Especially high failure rates (about half of all faults) occur in the climate chamber tests, but in the damp-heat and thermal-cycling tests in particular (Fig. 1). The damp-heat test accelerates material corrosion and often results in noticeable discolouration or voids in the encapsulation material, indicating the unsuitability of polymeric materials and adhesives. Delamination at the interfaces

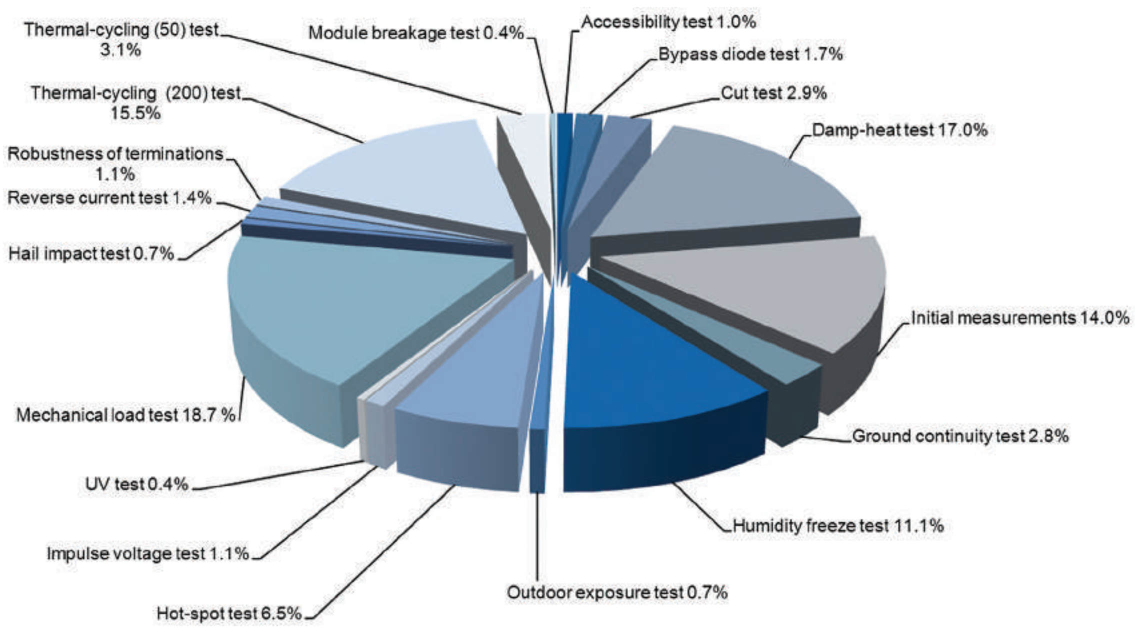

Figure 1. IEC 61215: failure distribution in the certification of crystalline PV modules.

between materials is also a major cause of failure. (Test conditions: 85°C/85% RH, 1000 hours.)

The thermal-cycling test is basically a mechanical fatigue test, in which differential thermal expansion may cause cells or interconnects to crack. This test can also address any thermal mismatch between components. (Test conditions: 200 temperature cycles between −40°C and +85°C, current injection for temperatures >25°C.)

> “Type approval tests do not guarantee that all manufactured PV modules will have the same quality as the tested modules.”

These type approval tests, however, do not guarantee that all manufactured PV modules will have the same quality as the tested modules. This guarantee can be obtained only from continued quality assurance at a high level. In particular, no material modifications may be made without further testing while keeping production processes the same.

The threat to fulfilling the demand for quality posed by the significant cost pressure and the search for inexpensive materials and procedures is not just a theoretical one. Unfortunately, negative operational experience and deficient quality are testifying to the reality of this threat to an ever-increasing degree. TÜV Rheinland seeks to counteract this trend by now performing production inspections, which were previously annual, more frequently, and also unannounced.

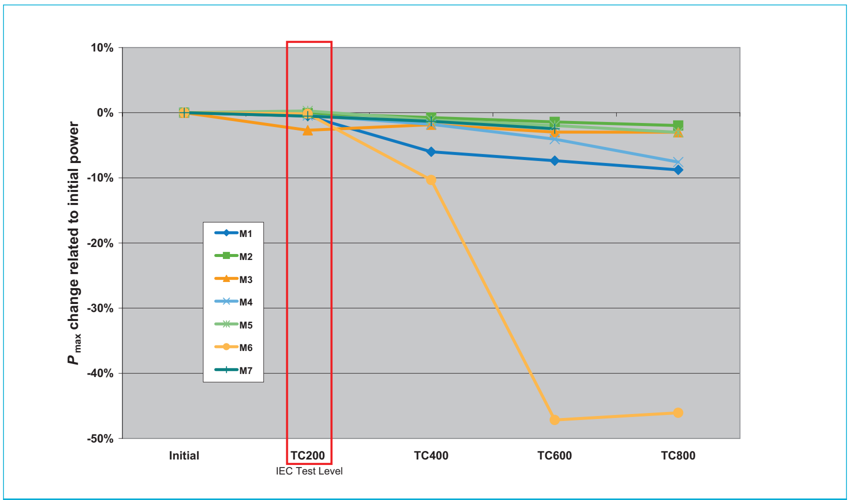

Figure 2. Maximum power degradation during an extended thermal-cycling test.

Can a PV module lifetime of (for example) 25 years be derived from the IEC tests if passed?

The question whether a module that has been certified in accordance with IEC 61215/61730 has a service life of 25 or more years cannot be affirmatively answered, according to the current state of research; nor does the lifetime issue form the background of these standards. Failures occurring up to the end of service life are not covered by these test procedures. Furthermore, the time of the end of life cannot be determined or predicted. Because of the complex stress placed on PV modules during long-term outdoor exposure, no informative and practical test seems to be foreseeable at present. If the acceleration factors are too high, the results will become too far removed from actual exposure conditions and actual ageing. Another

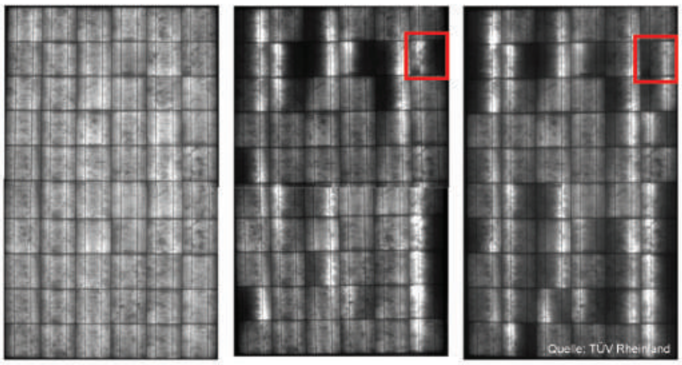

Figure 3. EL images of a module during an IEC temperature-cycling test: 200 cycles (left), 400 cycles (centre) and 600 cycles (right). For the cell outlined in red, the crack of the cell connector after TC400 could not be verified after TC600.

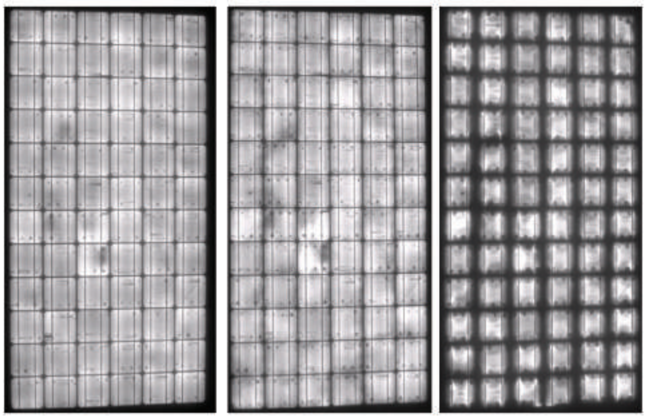

Figure 4. EL images of a c-Si module in extended damp-heat testing: 1000 hours (left), 2000 hours (centre) and 3000 hours (right).

possibility is to develop ageing models for the materials employed in the module group, and to verify and validate these models through concrete operational experience over several years. However, it must be assumed that other material combinations and manufacturing procedures will continue to be used in the construction of modules until these results become available. The present situation is such that even future test procedures will never allow an exact determination of the service life in acceptably short periods of time.

Accelerated laboratory testing (thermal cycling and damp heat)

For the further analysis of degradation mechanisms, the two aforementioned climate chamber test methods (thermal cycling and damp heat) are currently being used in extended test cycles and discussed. The idea being pursued is to estimate the risks to lifetimes via comparisons of the results of the extended test sequences when different module types are used.

Accelerated thermal-cycling testing

In order to study the degradation processes due to thermal cycling, extended temperature-cycling tests were conducted on seven c-Si PV modules, with intermittent diagnostic measurements at 200, 400, 600 and 800 cycles. Fig. 2 shows the measured power degradation curves for the seven test samples: the modules clearly fulfil IEC 61215 test requirements (TC200). Extended qualification testing revealed that more than 400 cycles were needed to observe failures in the interconnection circuit. At the end of the test, three modules still satisfied the IEC 61215 requirements after TC800.

> "Tests have shown that breakage of cell connectors is the prevailing degradation mechanism in thermal-cycling tests of c-Si modules."

Tests have shown that breakage of cell connectors is the prevailing degradation mechanism in thermal-cycling tests of c-Si modules. Electroluminescence (EL) analysis proved to be the appropriate method for identifying cracks in internal wiring, but may not find all failures in the cell interconnection circuit. As an example, Fig. 3 shows EL images of the module with the highest power degradation, taken at 200, 400 and 600 temperature cycles. Variations in brightness across the cell area indicate inhomogeneous current flow between the busbars. The darker parts indicate reduced emission of light and can be interpreted as interruptions or reductions in the current flow (increase of contact resistance) to the adjacent cell, so that breakage of the relevant cell interconnect may be assumed. A comprehensive evaluation of the EL images revealed cracks in 31 cell interconnects for this particular module after TC800. Other modules showed less than 10 disconnections after the same number of temperature cycles. Three of the modules showed no defects at all.

Accelerated damp-heat testing

The EL images in Fig. 4 show an example of degradation behaviour of a c-Si module taken after 1000, 2000 and 3000 hours of

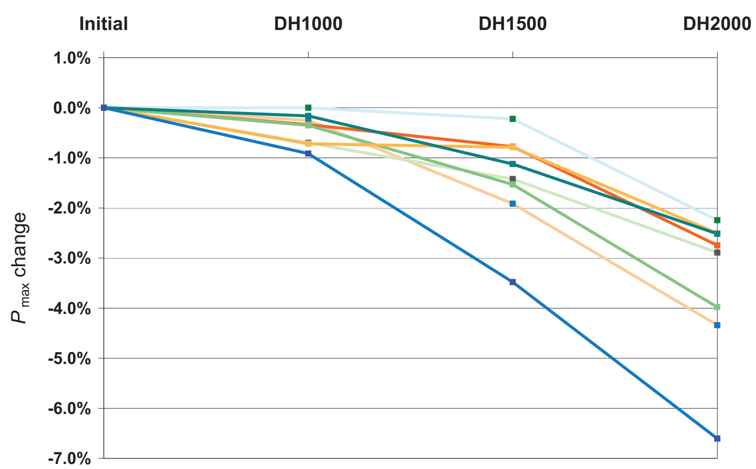

Figure 5. P_{max} change for extended damp-heat testing of eight modules from a production lot of the same type.

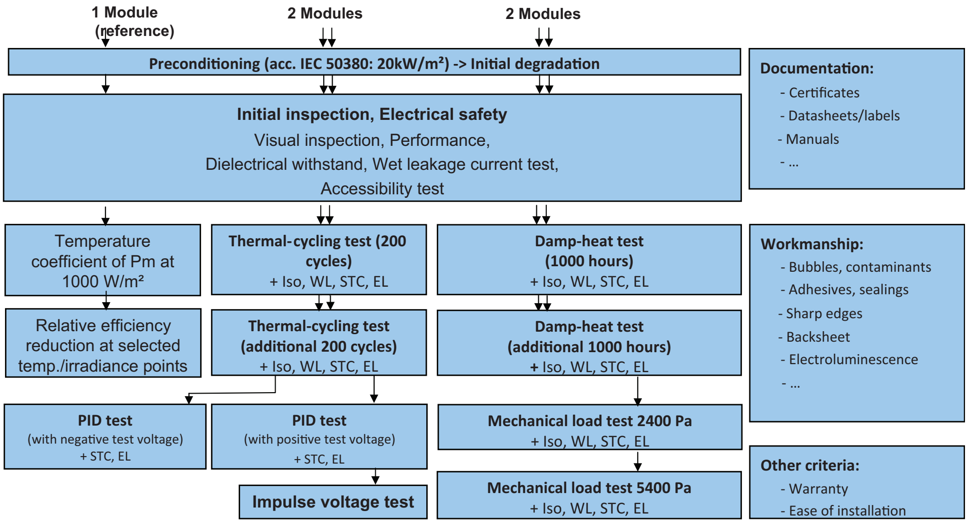

Figure 6. Test sequence of PV+Test.

extended damp-heat testing. Changes in EL records were mainly observed for test durations above 2000 hours. The dark areas around the cells indicate inactivity possibly caused by corrosion and water vapour diffusions across the spaces between cells. This finding is also reflected in the measured power degradation of −1%, −4% and −28%, respectively, for the intermittent measurements.

The finding that material degradation is accelerated after 2000 hours of damp-heat exposure was confirmed in a second test series, in which eight modules of the same type and from the same production lot underwent 2000 hours of damp-heat testing. This test run investigated the variations in degradation for identical test samples. Fig. 5 shows the power degradation curves resulting from intermittent measurements after 1000, 1500 and 2000 hours. For standard damp-heat testing, the spread of data points lies between 0 and −1%. The total spread increases with testing time, however, and reaches 2% after 2000 hours (seven modules), with one module showing a higher degradation.

Taken in isolation, the results of the extended damp-heat and temperature-cycling tests offer no particular gain in knowledge, since, as already noted, they bear no relationship to the actual lifetimes of the modules. On the other hand, these results are valuable if they can be evaluated by benchmarking against other products. Of course, PV modules that yield good results in the extended tests pose a lower risk of either an early failure or a failure to achieve the desired lifetime.

Benchmarking tests provide reliability and reduce the risks of failure

Previous applications of quality assurance systems through tests and inspections in the production of PV modules have indicated the following basic weaknesses:

- IEC tests alone are not sufficient for reliable predictions of lifetimes. Only expanded ageing tests will increase the store of knowledge through comparisons of different PV module types.
- Given the changes in materials and processes, as well as deficient quality in production, the quality of all manufactured modules does not always correspond to the quality of the certified product. Nor can this correspondence be ensured through intensive inspections during production.

These weaknesses can be redressed through methods of market observation, and more stringent (expanded) tests and comparative assessments, since manufacturers can gear themselves to these quality requirements.

PV+Test established as the benchmark for PV modules in the market

A benchmark test developed by TÜV Rheinland and Solarpraxis – the PV+Test – offers a suitable supplement

Figure 7. Test mark of the PV+Test.

to quality assurance and implementation, in particular for informing the end consumers (Fig. 6). Unlike the certification tests, the PV+Test is performed on modules purchased on the market. Since the number of such modules sampled will of course be very small, the manufacturer must establish 100% quality assurance in production as much as possible, in order to avoid the risk of subsequent failures.

> "Unlike the certification tests, the PV+Test is performed on modules purchased on the market."

The PV+Test already takes into account the extension (doubling) of the damp-heat IEC test to 2000 hours and of the temperature-cycling IEC test to 400 cycles, in accordance with the ageing requirement explained above. The test conditions are therefore more stringent than in the IEC test. Other tests necessary for non-disrupted system operation, such as a potential-induced degradation (PID) test with positive and negative voltages, are added. Finally, the ease of assembly is evaluated as well as the data sheets and assembly instructions.

If agreed to by the manufacturer, the results of the PV+Test are published in the two professional journals *Photovoltaik* and *PV Magazine*. This system leads to a 'best-of' list, providing a good basis for planners, installers and investors for estimating quality, since it contains high-quality, marketable products. The quality of the published modules is also indicated by the fact that nearly 50% of the manufacturers do not regard the test results as meeting their own demands and therefore have not agreed to publication.

From the high-quality PV module to the professional and suitable PV system

Not only is the quality of the PV modules important, but also the quality of planning and installation of the overall system poses high risks for long-term protection of profitability. However, the influential factors for the financial risk are not limited to the technical- and safety-related risks. The risk assessment of photovoltaic projects must also include, as well as the political risks, an evaluation of the location regarding on-site risks, and an evaluation of the logistical risks in connection with the installation of the system (Fig. 8). The totality of these risks associated with the PV project are essentially borne at first by the project developers and the investors.

Figure 8. Types of risk.

To understand the distribution of risks and the previous quality-assurance measures, it is helpful to first look at the different motivations of the players in the project and market in terms of the required or accepted quality levels.

Module manufacturers are interested in placing their products on the market with manufacturing costs that are as low as possible and at prices that are either as high as possible or – in difficult market phases such as the current one – at least reasonable. In the long term, the margin must be such that research and development can be financed along with constantly improved quality control, as well as allowing capacity to be expanded and production processes to be optimized. Especially crucial for quality at the module manufacturer's end is that the number of complaints and warranty cases needing to be dealt with is as low as possible. High complaint rates pose a serious problem not only for the financial position of the company, but also for the reputation of the brand. Moreover, returns from the market cost many times the price of quality improvement in production. There is also the desire to position the company in a positive way among competitors through unique selling points. Besides technological leadership (concerning efficiency, for example), statements on quality and verification of quality are also regularly mentioned in this regard.

Wholesale dealers are very often involved in warranty processing. In the event that they are importing the modules themselves into the EU, these dealers will also be affected by product liability. Some established wholesale dealers have therefore developed strategies for lowering risks and for checking quality. These can range from auditing the manufacturers to taking random performance measurements and carrying out visual inspections or EL imaging for micro-crack and cell fracture detection. Test procedures, including ageing tests in climate chambers, are already being performed to some extent: these tests are conducted partly by the wholesale dealers and partly by test centres on behalf of the wholesale dealers.

To the extent that they procure the modules or import them themselves, **installers** generally do not have the resources for testing quality. They must therefore resort to other sources of information, such as the PV+Test when selecting high-quality modules, and to any possible long-term experience.

Engineering procurement construction contractors (EPCs) are subject to higher risks regarding system quality and any stated assurances as to the energy yield, and should therefore have an interest in high-quality components and qualitative conformance. At the same time, experience has shown that serious errors in planning and installation affect photovoltaic plants to varying degrees. In the best-case scenario, these errors will result in only the consequential costs of rectifying the defects. The worst case, however, may involve high material damage or even personal injury. For this reason, inspection of the plant by a third party is often required.

Investors generally bear the highest risk in the long term and therefore have a strong interest in high system quality. Of course, given the lack of knowledge and experience in this market segment, not every investor

(a)

(b)

Figure 9. Damage to a PV system: (a) from ground subsidence; (b) from fire.

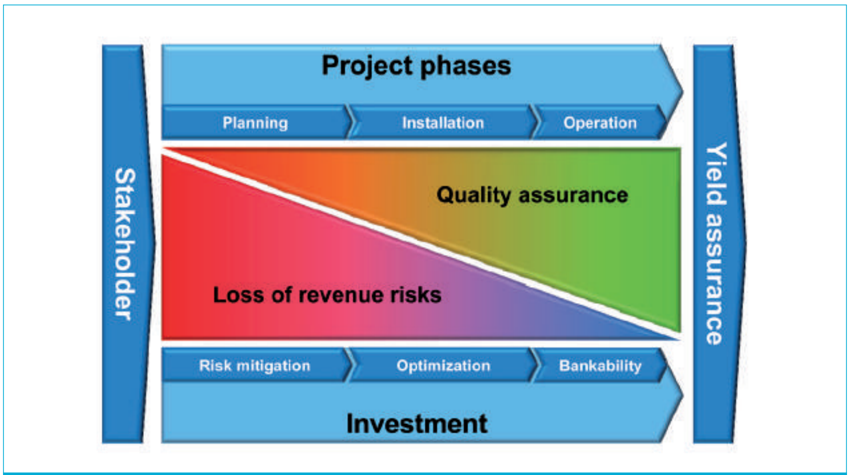

Figure 10. Quality assurance for PV power plants.

Figure 11. PV power plant inspection/TÜVdotCOM certification of a PV power plant.

can have an overview of the risks. For example, performance guarantees by the manufacturers alone are no guarantee that the expected return on investment will be realized. Since the systems are often planned and set up under considerable time pressure, the installation quality of each system again poses a high risk potential. Moreover, the striving towards the absolute minimum price at the cost of quality cannot be fully offset by PV insurance policies. The latter can be cancelled by the insurance company following damage claims or at the end of a minimum term. In the case of systems experiencing serious defects it must therefore not be assumed that the desired return on investment can be achieved in the long term. In this event, too high a loss may therefore be incurred by the investor. Given this overall situation, each investor is emphatically advised to bring in a third party to accompany the project. With its international network, TÜV Rheinland naturally has an outstanding reputation in this service and is generally recognized by all project parties.

Banks focus primarily on the credit standing of the credit receivers and on the cash flow of the PV power plants. The investors are themselves responsible for their expectations of return. Nevertheless, the banks require a wide range of technical tests and verifications to be performed. While certain banks are content with some basic information, others maintain a 'white list' as a positive list for components or EPCs. They partly comprise a considerable number of preliminary tests or tests accompanying the implementation of the PV system.

Insurance companies more or less safeguard the profitability of the PV power plants, depending on the insured risks. The quality of the components and of the installation of the PV plant is therefore vitally important. After all, high payments will still be due if the yield is low or if defects and system downtimes occur. At present the insurance companies are complaining about an exorbitant increase in damage cases attributable to inferior-quality components or faulty installations.

From bankability to insurability

As expected, the notion of bankability focuses on the role of banks, with the following definition being comprehensively applied: a bankable PV project (the set-up and operation of a PV system) requires diligence in legal, technical and economic matters to ensure the success of the project. However, there is no common understanding of the term 'bankability,' nor is there a universal standard applied. Bankability of course extends from the PV system itself to all component manufacturers and EPCs. Part of this overall bankability idea, pertaining exclusively to the banks themselves, concerns technical bankability, in the assessment of which TÜV Rheinland can be an excellent partner.

In the future, the quality assurance system resulting from the consideration of technical bankability will be largely driven by the insurance companies, since the remaining technical risks will be covered by insurance companies, leaving only a calculable risk for the bank.

Module tests for technical bankability

For the module types used, initial tests that generally go beyond the IEC tests may be required. TÜV Rheinland offers a standard procedure that can be adapted at the request of banks and investors and which should be regarded as a preliminary qualification in advance of definite projects. In this regard, factory inspections are often required as well.

Figure 12. Infrared inspection to detect hot spots.

Alongside the PV projects or large-scale PV power plants, sample testing is also possible, either in planning or during implementation. The latter deliberately dispenses with time-consuming tests in the climate chambers, so that the results can be made available very quickly during the project – for example, within two weeks. These tests present a good opportunity for quality control, since material combinations of modules from the production lots that will be actually installed in the PV system can be tested. This significantly increases the informativeness of testing. A reasonable scope of testing is generally reckoned to be power determination, light-soaking for determining light-induced degradation (LID) and low-irradiance performance for validating simulation computations of the energy yield. EL imaging allows the detection of micro-cracks and cell breakage, as can occur in improper manufacture or during transport. Electrical safety can be briefly checked by insulation tests and wet leakage current tests. Testing the modules for PID can help avoid subsequent power losses that might otherwise result from interconnections of the modules as strings, depending on the inverter topology and earthing concept. Finally, hot-spot tests, gel-content tests and rip-off tests may be added on request.

In all these tests the power determination for a suitable number of PV modules (depending on the system size) is extremely important, since the actual performance levels of the modules often do not correspond to the guaranteed performance.

"The high quality of modules and other components on its own is no guarantee of the economical operation of a PV plant."

System checking

The high quality of modules and other components on its own is no guarantee of the economical operation of a PV plant, since professional planning and proper installation are also crucial. Power plant inspections are especially indispensable for large PV power plants. Depending on the desired scope, these inspections can take place during the entire project – from the planning phase and the monitoring of construction during installation, to the monitoring of the plant in the operational phase.

In the evaluation and planning phase, defects that are only rectifiable at significant cost later on can be avoided by verifying energy yield computations, performing a site evaluation (including shading analysis) and checking the plant specifications. The planning review of outdoor plants requires a geological survey and static verification for the foundations of the mounting systems and statics. These documents must be checked for plausibility. The same applies to the optional construction monitoring, which can detect problems early enough for possible rectification without extra costs. Experience shows that most errors are made in carrying out the construction work. Spot-checking of module performance in the laboratory with high measurement precision and with optional construction monitoring is an important element of the installation phase.

The technical plant inspection includes the following:

- Safety-related inspection
- Comparison with the specification
- Verification of the functioning of the entire plant
- Power measurements of single strings
- Infrared inspections of module and generator connection-box samples
- Measurements of the layer thickness of coated mounting parts

The economical operation of a PV power plant requires plant monitoring, which can be performed by a service provider such as TÜV Rheinland. Regular inspections of the plant and plant safety – as well as inspections that are due before the end of warranty periods, product warranties or stages in performance warranties – form an often-neglected part of quality assurance.

Summary

Quality need not be expensive; on the contrary, suitable quality assurance pays off and leads to a higher return on plant investment. It is reasonable to use an integrated concept for preventing multiple measurements and qualifications. This concept begins at the production site of the modules and other products, and must focus on the quality of each individual manufactured module, in addition to certification. A regular inspection of PV modules on the market in the context of benchmarking (PV+Test) will yield information about achieved quality levels which will be understandable by installers and end consumers. While benchmark information on expanded ageing tests (damp heat and temperature cycling) provides no concrete details about the lifetimes of PV modules, it does help in minimizing the risks and in attaining higher lifetimes of more than 25 years.

Besides PV module qualification, PV plant qualification is extremely important. In the foreseeable future, the insurers – as well as the investors and professional operators – will impose requirements aimed at significantly higher quality levels. Plant monitoring and maintenance must be given considerably more importance; this, of course, also applies to small power plants. A comprehensive quality assurance system must also clearly cover transport and logistics, both in the worldwide flow of goods and at the construction site. The coordination and reliable documentation of module data during production, and stress documentation during transport to the construction site, can verifiably establish the condition of the product up to the time of installation and thereby avoid the problem of repeated multiple qualifications.

About the Authors

Ingo Baumann is an energy and environmental engineer, specializing in renewable energy. He has been working for TÜV Rheinland Solar Energy in Cologne as a senior expert in innovative services since 2011. Previously he worked for three years as a product manager in solar modules and as a strategic purchasing team leader of PV modules at Energiebau Solarstromsysteme GmbH Cologne. He also spent more than six years at MHH Solartechnik GmbH Tübingen, beginning in the sales office and then progressing to head of the product management and purchasing department.

Willi Vaassen has been working in the TÜV Rheinland Group in the field of renewable energies for 30 years. As a business field manager he is responsible for the operation of a PV test laboratory, applied research, plant acceptance testing, and qualification testing of solar thermal components and systems.

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Driving down BOS costs in commercial installations

Ethan Miller & **Alexander Griffiths**, Mainstream Energy, San Luis Obispo, California, USA

ABSTRACT
This paper provides an overview of reducing the 'soft costs' of solar, with a focus on driving down the cost of balance of system (BOS) and operations, primarily in commercial-scale installations. Attention is drawn to the internal data and information on specific case studies/best practices that can be replicated by other companies. Mainstream Energy (which supports three business units – REC Solar, AEE Solar and SnapNRack) aims to simplify system design and configuration by utilizing new technologies and streamlining internal processes to reduce total system cost – and take solar to the mainstream.

Introduction

Amid global market uncertainty, the US solar market remains a bright spot. Residential, commercial and utility customers are on pace to install a record amount of solar in 2012, totalling more than 3.2GW of new capacity by the end of the year. In the second quarter of 2012, the USA added 742MW of PV installations – a 45% growth over the first quarter of this year and a 116% growth over the same quarter a year ago, according to a recent report from the Solar Energy Industries Association and Greentech Media Research [1].

> "The solar industry must identify more cost drivers that will reduce the cost per watt in order to be competitive with traditional fuels."

Some growth can be credited to rapidly falling module prices, which have dropped by 80% over the past few years and consequently decreased the overall cost of solar, spurring new installations. But as the solar industry looks to continue its impressive expansion, it must identify more cost drivers that will reduce the cost per watt in order to be competitive with traditional fuels. Low module prices alone are not enough to ensure industry success.

To cut costs further, solar developers must look elsewhere. Modules represent only 40% of system costs, and that percentage is shrinking. Soft costs and balance-of-system (BOS) costs have not decreased at a similar pace. In the past two years, these costs have actually increased by 3 to 5% as a percentage of total system cost, leading many in the industry to either advocate improvements in BOS components or investigate ways to streamline the permitting process to cut costs. These are important components, but a truly comprehensive cost-reduction strategy must include an entire-system approach to cost. This approach integrates innovative new BOS technologies, optimizes the construction and project development processes, and decreases the soft costs of solar (such as permitting, human resources activities, transportation and training) to promote end-to-end operational efficiency. In turn, this operational strategy allows solar system integrators to further bring down the overall cost of solar, enhance system value and ensure continued market growth.

Figure 1. A 1.1MW single-axis tracking system installed at the City of Hayward Water Pollution Control District in California.

Additionally, this approach offers value beyond the cost per watt. That metric can be misleading and overly simplistic, undermining other value-added parts of a system, such as reliability and overall performance. Cost will always be a core driver, and it is proposed that the complete cost picture be looked at – including system lifetime, maintenance and efficiency. Moreover, installers and system integrators who attack cost drivers to meet market expectations without compromising quality can differentiate themselves in an increasingly commoditized marketplace, with system reliability and durability emerging as key metrics when evaluating value.

Driving down costs beyond the module: BOS innovations

BOS components represent a key area for cost reduction, especially given the potential impact on labour. Effective BOS utilization can result in lower parts count, lower commodity costs and increase speed of installation. Making informed decisions on things like technology, product quality, product life span and part count will directly affect other project cost drivers such as labour and subcontracts. These components also play a key role in market differentiation, as they allow installers to remain competitive in a marketplace that is increasingly focused on dollars per watt. Using the right technologies can increase a system's energy output and boost reliability while improving a project's levelized cost of energy (LCOE). For example, a horizontal single-axis tracker could increase system production by about 20%; however, additional operations and maintenance costs could quickly erode profits if reliability is compromised.

> "BOS components represent a key area for cost reduction, especially given the potential impact on labour."

Mounting and racking systems can significantly streamline the number of BOS components and materials used in an installation, as well as reducing the amount of associated labour. Accounting for as much 10 to 15% of a system, new mounting and racking products provide a myriad of improvements, from self-ballasted and weighted systems that reduce the number of rooftop penetrations, to prefabricated systems assembled offsite that cut down on labour and inventory. If a racking system requires penetrations through the roofing membrane, a roofing contractor will typically be brought in to install flashings and maintain any warranties that may exist. Typically these costs can substantially inflate racking. Likewise if field labour costs are high, the contractor may opt to assemble portions of the system offsite with lower labour costs and higher efficiency, and then ship in the completed assemblies.

Ballasted and weighted systems are becoming increasingly popular with large commercial customers, such as big-box retailers like IKEA, to streamline the installation process, preserve rooftop structural integrity and cut overall costs. These systems allow installers to approach zero penetrations, depending on a full structural analysis. For a 1MW system, Mainstream Energy has achieved a 90% reduction in the number of penetrations, which is especially attractive to large-scale commercial customers. Recently, a big-box retailer wanted to install a large solar system that required a racking solution that reduced the number of penetrations. As the engineering team sought to secure the system without penetrations, the installation company identified a new solution they could use for other projects facing the same issues. The new product had minimal penetrations, using instead the weight to hold down the system.

Modular racking systems can be prefabricated and assembled offsite, reducing field construction labour and total part count. This means that the installation process is simpler, resulting in fewer mistakes, a faster install and less time devoted to inventory management. Additionally, prefabricated systems can benefit from greater component standardization, such as wiring. With a prefabricated wiring-harness system, fewer hours are required on site for measuring and slicing wire.

Electrical system considerations

Electrical systems optimization is a critical element in driving down costs while maintaining performance and reliability. Electrical code dictates much of the equipment utilization; however, through new innovations and code interpretation, there is significant opportunity here.

Credit: SnapNRack

Figure 2. Delivery of preassembled racking and modules to the site for installation (the North Carolina Progress Energy II project).

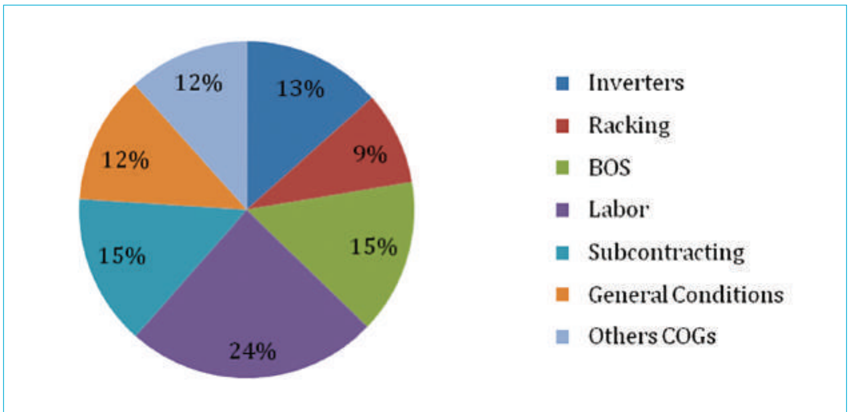

Figure 3. Cost distribution of a commercial system. (Other costs of goods (COGs) sold include permits, warranty, freight, bonds and consumables as primary items.)

Inverters require a different set of considerations than other system components, and each new product on the market raises questions about efficiency, uptime and the type of warranty offered. For larger systems, a simplified system design that uses high-voltage inverters represents the lowest cost option. This is true with both AC and DC wiring. For example, significant electrical cost can be saved in commercial and utility-scale ground-mounted systems by switching from a 600-volt inverter to a 1000-volt inverter. This lengthens the string of modules and reduces the number of BOS components needed. Additionally, through the use of module-level technology such as optimizers, string length can be increased by up to 30%, further reducing electrical equipment and labour costs.

Optimizing activity at the installation site

The greatest single expense for a commercial system is labour (Fig. 3). When combined with basic general conditions, this can represent up to 36% of total system cost. Companies that can minimize labour and general conditions – such as rental equipment, travel and fuel – will be able to offer the lowest cost system and achieve highest profitability.

> "The greatest single expense for a commercial system is labour."

The construction process provides several opportunities for driving down costs. In the case of ground-mounted systems larger than 500kW, adjusting foundation types can streamline installation and further reduce the labour hours required for a project by up to 20%.

A typical process for installing foundations for ground-mounted systems involves drilling one-foot diameter holes four to six feet deep, and then placing vertical posts and pouring concrete. Not only is this time intensive (on average fewer than 70 to 90 installations per day), but it also requires trucking/shipping materials over long distances. Partnering with pile-driving companies eliminates concrete and allows an installer to improve labour times and complete the system faster (on average 150 to 200 installations per day). By eliminating the need to procure pile-driving equipment and transport it to the site, REC Solar realized

Figure 4. Cost management system.

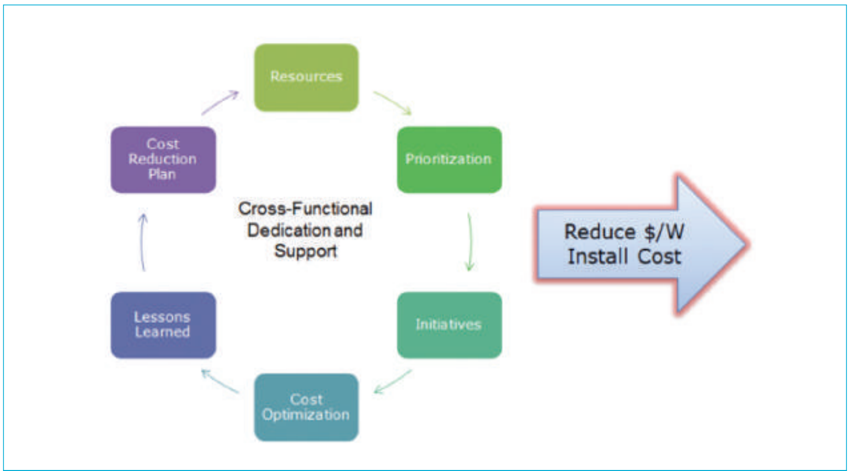

Figure 5. Continuous improvement.

significant savings and reduced overall general conditions (i.e. all ancillary project costs, such as equipment rentals and transportation). Over a two-year period, REC Solar realized savings of over 30% of foundation costs when performing pile foundations vs. concrete foundations.

The final step: attacking soft costs

An end-to-end approach to achieving operational efficiency takes account of component improvements that cut back on inventory as well as on-site labour hours, and considers optimized soft costs that improve operations. The cost of a solar system is not just in the modules – it is also in hotels, rental equipment, transportation costs, installer training and the per diems for the installation crew. It is in lead generation, sales teams, system design and engineering, and product procurement. Soft costs have become so important that the US Department of Energy's SunShot Program recently opened a $10 million competition in search of innovative business practices that reduce the soft costs of solar to $1/watt.

The overall goal of improving internal processes is to build a job faster and at a lower cost. This process starts when a job is first bid. REC Solar has implemented a process where the project's demands and milestones are openly discussed, with a special consideration for the tools and products needed to reduce mistakes in the development process and eliminate reworking. Project transparency helps line up the right resources quickly while streamlining internal processes. A successful organization has an effective system in place for cost management to provide regular forecasting and corrective action by the project team (Fig. 4). These systems are also evaluated within the ecosystem of cross-functional internal processes, including prioritization, company-wide initiatives, resources and lessons learned (Fig. 5). This helps determine the best steps to take to reduce cost while considering company-wide impact.

> "Project transparency helps line up the right resources quickly while streamlining internal processes."

Company dedication to continuous improvement is crucial, and should be circulated via feedback loops and open sharing that discuss lessons learned after the completion of each project. Instituting best-practice and lessons-learned communications through company newsletters, meetings and so on will ensure that this becomes part of the organization's culture.

Conclusion: how can the industry continue to drive down costs?

To maintain growth, the solar industry must continue to focus on driving down lifetime costs of solar beyond the modules, by focusing on BOS innovations, construction efficiency and soft costs.

> "The industry needs to move towards products and processes that boost reliability and performance."

Apart from the areas outlined above, there are additional opportunities for attacking cost and improving the overall value of solar installations. The industry must look to developing standards around components – such as wiring, racking, bolts and mounting equipment – which will further streamline system design and installation. Pushing for a universal permitting process will also cut the soft costs of solar further. More importantly, the industry needs to move towards products and processes that boost reliability and performance, and use these terms to shift how it evaluates system cost.

Reference

[1] Solar Energy Industries Association & Greentech Media Research 2012, "U.S. solar market insight report: Q2 2012", executive summary.

About the Authors

Ethan Miller is vice president of operations for Mainstream Energy and oversees logistics, procurement, engineering and construction for both Mainstream and its subsidiaries – REC Solar and AEE Solar. During his time with the company, Ethan has managed construction of more than 8000 projects, including complex utility and government projects. Additionally, he manages the supply chain, supporting procurement and logistics as well as the distribution to AEE Solar dealers and REC Solar projects. Ethan holds a B.S. in mechanical engineering from California Polytechnic State University.

Alex Griffiths is a project development engineering manager, overseeing all of REC Solar's commercial project development engineering, which totals over 1500 systems. He helps coordinate efforts between the commercial sales and engineering teams to develop the best solar solutions for customers. Alex has a degree in general engineering from California Polytechnic University, San Luis Obispo, and is also active in many professional organizations, such as the Association of Energy Engineers (AEE).

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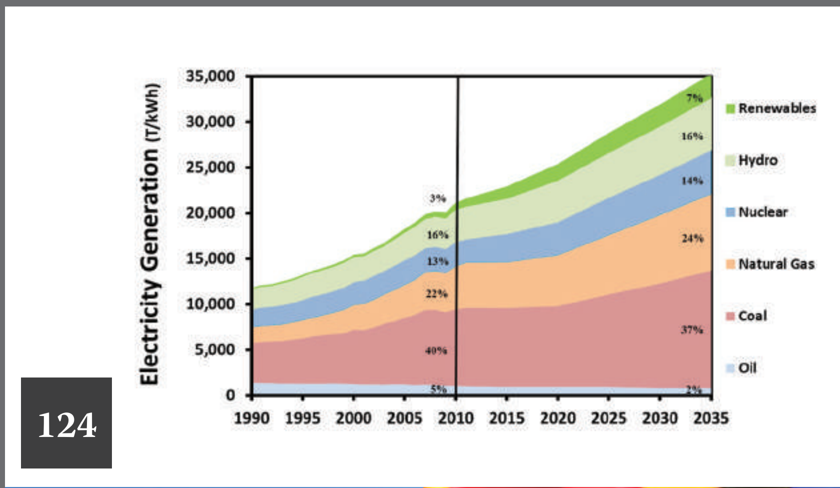
Market Watch



WTO to rule against Ontario in FiT dispute

The World Trade Organization (WTO) was due to rule that the Canadian province of Ontario's feed-in tariff violates WTO non-discrimination policy as Photovoltaics International was going to press.

The Geneva-based International Centre for Trade and Sustainable Development revealed details of the pending decision a confidential WTO report, which said that the body would uphold EU and Japanese complaints that the Ontario FiT's domestic content policy breaks international trade rules.

A spokesman for the WTO said it could not comment on the leaks.

The Ontarian feed-in tariff includes a domestic content requirement of at least 60% in order to qualify for subsidies and grid access.

Financial and Business News Focus

Analysts continue to question Applied Materials presence in solar industry

The significant collapse in sales within Applied Materials' Energy and Environmental Solutions (EES) division – which houses its solar equipment product range – is being questioned by financial analysts as the company continues to absorb losses rather than exit the sector altogether.

Applied Materials said in its FYQ4 2012 conference call that it took a goodwill impairment charge associated with the EES segment of US$421 million in the quarter. Management said that this was due to the solar equipment sector's deteriorating market conditions that included customers' financial health and "reduced market valuations".

ESS sales for the full year were US$425 million, down 79% year-on-year.

However, management also warned that sales would be down more than 30% in the next quarter for its EES division.

According to Citi financial analyst Timothy Arcuri, Applied's EES division operating expenses would be around US$30 million per quarter after restructuring, around US$120 million per annum, requiring annual sales of US$500 million just to break even.

This suggests that Applied may de-emphasize wafering or offload the technology in the future as a rebound in capacity additions could take several more years to materialize, long after a new technology buy-cycle for equipment and materials needed to boost cell and module efficiencies is in full-swing.

Taiwan-based PV manufacturers, Neo Solar Power (NSP) and DelSolar are to merge, creating the largest solar cell company, on a capacity basis, in Taiwan.

Neo Solar Power and DelSolar to become major solar cell producer in merger deal

Taiwan-based PV manufacturers Neo Solar Power (NSP) and DelSolar are to merge, creating the largest solar cell company, on a capacity basis, in Taiwan.

Delta Group said that based on a successful tender offer by NSP to acquire up to a 15% stake in DelSolar as part of the merger acquisition, the firm could participate in fund raising activities of the combined entity to the tune of NT$1.5 billion.

According to a statement from Delta Group, NSP has a solar cell capacity of 1,300MW, while DelSolar has a cell capacity of 600MW.

The newly merged entity would have a cell capacity of nearly 2GW, making it the largest solar cell manufacturer in Taiwan and second largest on a global basis.

LDK Solar receives NYSE delisting warning

Struggling PV manufacturer LDK Solar has received a delisting notice for its American depositary shares on the New York Stock Exchange having seen the value of the shares fall below the US$1.0 threshold in October 2012.

The delisting notice was triggered after LDK's shares traded below US$1.0 for 30 consecutive trading days through November 5, 2012.

The company said that it would "cure this deficiency within the prescribed timeframe", which is six months from receipt of the notification.

Consortium secures funds for two 75MW South African PV systems

A consortium of three companies – US PV developer SolarReserve, financial services company Kensani Group and South African renewables developer Intikon – have closed a financial deal worth R5.15 billion (US$586 million) to fund the development of two 75MW PV plants in South Africa.

SolarReserve, Kensani Group and Intikon Energy have closed a US$586 million finance deal for two 75MW projects in South Africa.

The 75MW Letsatsi project will be located in the Free State while the 75MW Lesedi Project will be constructed in the Northern Cape. The projects were selected by the South African Department of Energy (DOE) during the first round of bidding under the South Africa Renewable Energy Independent Power Producer Procurement Programme (REIPPPP).

Construction of the projects will be undertaken by a consortium led by ACS Cobra, along with Spain-based Gransolar and South Africa's Kensani Energy EPC.

Scheduled to complete by mid-2014, the projects are estimated to generate enough output to supply 50,000 households. Electricity generated from the projects will be sold to South African utility firm Eskom under 20-year power purchase agreements.

A percentage of revenues generated from the plants, estimated to be around R510 million over the life of the projects, will be set aside and invested in projects that will benefit local communities.

Yingli Green margins take massive hit in Q3

China's Yingli Green Energy has warned that it expects Q3 2012 gross margins to plummet on the back of inventory write downs, lower capacity utilization and countervailing and anti-dumping duties impact.

The company said that module shipments would be down 17% compared to Q2, while gross margins would be negative 22-24%. Excluding charges and duty provisions, margins would still have been between 0% and 1%, according to the company.

Inventory write downs are unsurprising as Yingli Green had noted in Q2 2012 that inventory levels had increased by approximately US$85.5 million to US$601.5 million in the quarter, with approximately 60% of inventories being classified as finished goods.

Although the company said that it margins would be impacted by the AD/CVD duties in Q3 2012, Yingli Green had noted in the previous quarter that sales in the US had fallen significantly (26%) compared to Q1. Sales in the US in Q2 were only 9% of sales

EU and China negotiating on trade despite solar disputes

European Commissioner for Trade Karel De Gucht has announced that the European Union will commence negotiations on trade market access with China.

Source: fotopedia

The Commissioner maintained that the first move to resolve the trade war would need to come from China.

This comes to the fore at a time when the EU and China are embroiled in what could turn into a trade war, with the two trading blocs launching tit-for-tat investigations into apparent solar equipment subsidies.

The commissioner said that China was a country "that wants to move up the value chain, so they are testing how far they can go and that results in a number of cases. I'm not interested in a trade war with China either…but if we have to impose duties we will do so".

Nevertheless, in order to resolve this situation where the Chinese have been accused to dumping solar panels in Europe, the Commissioner maintained that the first move would need to come from China.

Conergy pushing business in US and Asia as Europe wanes

Impacted by 40% module price declines, a tightening project finance environment and the cancellation costs associated with a wafer supply deal with MEMC, Conergy reported Q3 2012 revenue of €108.0 million, down from €182.4 million in the same period a year ago.

PV projects delayed due to financing issues for certain customers meant module sales were down 6% compared to the same period in 2011, to 84MW.

Yet the company was able to capitalise on a strong German market late in the third quarter as module volumes increased by 36% year-on-year, while volumes in Europe overall increased by 3% compared to the same period last year.

The decline in revenue was partially due to the continued fall in module prices and weaker demand across European markets. Management noted that module prices had fallen by around 10% quarter on quarter and 40% year on year, due to continued industry overcapacity.

Falling process also had an impact on gross margins. The company reported a gross margin of 16.5% for the first nine months of 2012, down from 19.7% in the same period of 2011.

The US market continues to experience strong growth as sales volume increase 51%, compared to the previous year period.

Report: 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.

In 2008 PV modules accounted for 67% of the average cost of a solar project. But, because of improvements in cell and module technologies, it is now BOS costs that are seen as problematic, accounting for 68% of a project's costs, the report said. As a result BOS manufacturers around the world are being squeezed, the report warned.

This process, however, will not be easy, requiring manufacturers to balance innovation with surety for customers, at the same time as minimising costs.

Source: Yingli

Yingli Green Energy has warned that it expects Q3 2012 gross margins to plummet on the back of inventory write downs, lower capacity utilization and countervailing and anti-dumping duties impact.

Australia to start 2013 without Solar Credits mechanism

The Australian federal government has announced the phase-out of its Solar Credits mechanism for small-scale, mostly residential, installations six months ahead of schedule.

The phase-out, effective January 1, 2013, comes shortly after the solar credit mechanism was reduced in July this year.

By 2014, the government estimates that the Solar Credits scheme will cost electricity consumers around 70% less than in 2012.

Source: Parliament of Australia

Greg Combet, Minister for Climate Change and Energy Efficiency, announced the phase-out of the Solar Credits mechanism.

The overall reduction in electricity bills is expected to be A$80 to A$100 million (approximately US$83 to 103 million) in 2013, according to government figures.

China anti-dumping investigation will stabilise polysilicon ASPs

The Chinese Ministry of Commerce's investigation of anti-dumping and countervailing into US, European and Korean modules will help Chinese polysilicon average selling prices (ASP) to level out in 2013, says market research company EnergyTrend.

Following an increase in the number of time-sensitive orders, as a result of the US investigation into Chinese cells and modules, EnergyTrend said it is optimistic that prices may begin to stabilize at a certain point. Multi-Si wafer ASPs dropped this week by around 1.15%, arriving at US$0.863/piece. For the mono-Si wafers, the extent of the price falls have been shrinking due to various manufacturers' halting production.

EnergyTrend advises Chinese manufacturers to turn their attention to Taiwan, another major PV supplying market with the largest production capacity after China. EnergyTrend also advises that business should adopt the inverted pyramid model, empowering employees who are closest to clients with more decision-making power, rather than those traditionally at the top.

Canadian Solar expects 50% of business to come from PV projects

Canadian Solar's CEO expects 50% of its revenue will be generated from its PV power plant project business in the next two years, marking a significant shift in its business model.

Dr. Shawn Qu, Chairman and Chief Executive Officer of Canadian Solar made the claim during prepared remarks in a conference call to discuss Q3 2012 financial results.

Dr. Qu noted the impressive growth the company had achieved this year in the ramp of its Total Solutions Business unit, which is responsible for PV project development and that the success of this venture would lead to 13% of revenue soon but is planned to become 50% of revenue over the next 12-24 months.

The company is following the increasing trend of major PV manufacturers such as First Solar and SunPower in increasingly becoming reliant on project business to generate revenue but importantly, higher margins than simply selling modules, due to severe price declines and diminished margins.

Asia & Oceania

Australia – Victoria

Victorian Energy and Resources Minister, Michael O'Brien, has backed a cut in Victoria's feed-in tariff. Effective January 1, 2013, the tariff will be A$0.08 (US$0.082) per kWh, which is down from the transition figure of A$0.25 (US$0.26) per kWh and a marked reduction from the original rate of A$0.60 (US$0.62) per kWh.

Bangladesh

Bangladesh receives an average daily solar radiation of 4-6.5kWh/m^2, with solar power installed in nearly 870,000 homes in rural Bangladesh.

The government of Bangladesh plans to increase power generation capacity to 16,000MW by 2015, of which at least 800MW is expected to be from renewable sources. However, the country does not seem to be implementing enough policies to be able to achieve this goal in the foreseeable future.

On the one hand, Bangladesh has one of the highest VAT/taxes on solar accessories and raw materials. Conversely, Grameen Bank has initiated a green energy credit scheme, although with a 10% interest rate, it is not affordable to most installers.

India – Tamil Nadu

The government of Tamil Nadu, India, has committed to generate 3,000MW of solar power by 2015 (1,000MW per year) through its newly launched Solar Energy Policy 2012, according to reports. All domestic consumers will be encouraged to put up rooftop solar installations with net metering facilities.

A generation based incentive of Rs. 2 (US$0.04) per unit for the first two years, Rs. 1 per unit for the next two years and Rs. 0.5 per unit for the subsequent two years will be provided for all solar or solar-wind hybrid rooftops installed before March 31, 2014. A capacity target of 50MW has been set up under this scheme.

Malaysia

In April 2011, FiTs were passed by Parliament. The 2012 tariffs were set by the Sustainable Energy Development Authority (SEDA) between MRY0.85 (US$0.28) and MRY1.25 (US$0.41) per kWh, expanded to a cap of 20MW in November.

The new capacity will be available to non-individual applicants who wish to build PV systems smaller than 500kW, with new applications to be accepted from December 17, 2012. The new quota for PV systems over 500 kW in size will be announced next year. SEDA also revealed that FiT incentives for PV will be cut by between 8% and 15% next year, pending government approval. SEDA has approved 362 applications for residential PV systems and 133 applications for non-individual systems since Malaysia introduced its FiT program last December.

Furthermore, SEDA announced that applications for its Solar Home Rooftop Programme will be accepted from September 24. The authority will allocate 2,000kW of solar PV for the fourth quarter of 2012 and 6,000kW for 2013 to homeowners. FiTs will range from US$0.40 for installations up to and including 4kW and US$0.28 for systems with an installed capacity of above 10MW and up to and including 30MW. Bonus FiT rates are also offered for BIPV installations and using locally manufactured products.

The FiT rates for all renewable resources (except for small hydropower) suffer from an annual degression rate of 9%, occurring at the beginning of each calendar year from 2013 onwards.

SEDA has estimated that homeowners could expect to get a return on their investment after six years, which could earn them an average of €163 per month for 21 years.

This program has allocated 2 MW of PV capacity for the fourth quarter of 2012 and 6 MW for all of 2013.

Taiwan

In June 2009, the Taiwan Legislative Yuan gave its final approval to the Renewable Energy Development Act to increase Taiwan's renewable energy generation capacity to 10GW within 20 years. Although the government reduced FiTs by a maximum of 10.3% compared with the second half of last year, US$0.25 to US$0.31 has been offered to roof-top installations and US$0.23 to ground-mount.

Thailand

Thailand was one of the first Asian countries with a comprehensive feed-in tariff, or adder, program. It enacted a 15-year Renewable Energy Development Plan (REDP) in 2009, setting the target to increase its renewable energy share to 20% of final energy consumption of the country by 2022.

The FiT has been in place for six years and gone through successive phases of adjustment, in response to higher-than predicted response by industry in the form of applications submitted for interconnection.

Solar PV systems are eligible for a FiT for a period of 10 years. The original THB8 per kWh (US$0.26) was reduced to THB6.5 (US$0.21) for those projects not approved before June 28, 2010. The original cap of 500MW was increased to 2GW at the beginning of 2012 due to high over-subscription.

Europe

Armenia

Armenia possesses significant solar energy potential with 2,500 sunny hours per year and an average annual solar radiation on horizontal surface of about 1720 kWh/m^2. A FiT rate of US$0.05 is offered to all renewables.

Denmark

Danish climate, energy and building minister Martin Lidegaard called for the expansion of Denmark's net-metering scheme, but a cut to the country's feed-in tariff.

Presented to the Folketing, Denmark's parliament, Lidegaard's draft bill has laid out plans to abolish the current ceiling of 6kW for solar power plants in order to encourage larger developments.

The proposal also includes cutting financial incentives by more than 50%. Lidegaard has asked that a temporary rate of DKK 0.130 (US$0.022) per kWh be offered for all solar installations as well as other small renewable energy plants. This rate will be gradually phased out to fall to DKK 0.60 (US$0.102) per kWh after five years.

Domestic PV installations in Denmark have grown exponentially in 2012 reaching 223MW this month from just 17.5MW at the end of last year.

Expected to come into force in 2015, the minister intends to reassess the level of support annually from 2018 onwards.

France

France's Ministry of Ecology, Sustainable Development and Energy is proposing a 10% bonus for commercial facilities with panels made in Europe. The government is also calling for tenders for large rooftop installations (over 250kW) to be launched later this year in order to promote innovative technologies and local economic development. The annual decline rates will be capped at 20%, states the Government.

In October, the French Energy Regulation Commission (CRE) fixed its FiT to €0.035 (US$0.045) and €0.075 (US$0.097) for the fourth quarter of 2012, having fallen from €0.045 (US$0.058) and €0.095 (US$0.123).

Greece
The Greek Parliament has approved a tax on revenue generated by renewable energy systems as part of a raft of austerity measures enacted to ensure Greece's place in the EU. PV systems installed before 2012 will be taxed by 25%, while PV systems built from January 1, 2012 onward will be taxed at 27%. Under certain conditions, the 27% tax could grow to 30%. Revenue generated by other types of renewable energy systems, including wind, biomass and hydroelectric, will be taxed at 10%. The Greek Association of Photovoltaic Energy Producers (SPEF) claims the measure will drive many small- and mid-size solar companies out of business because they will not be able to repay bank loans.

Italy
The Italian Ministry of Economy and Industry has opened a public consultation on its recently approved new National Energy Strategy. The proposed strategy confirms the Government's intentions to stop PV subsidies completely when the Conto Energia V programme hits its cap. Currently, just €242 million out of the €6.7 billion budget allocated to the incentive programme remains.

Poland
Poland looks set to ramp up its support for large solar plants through a new feed-in tariff and a green certificates programme in a bid to meet European Union 2020 renewables targets.

Poland's Institute of Renewable Energy's analysis of the implementation of financial incentives for renewables lists the FiT for installations larger than 100kW as US$0.337 for 15 years. Poland's current Green Certificate scheme witnessed a boost in investments since its launch in October 2005. Each tradable certificate, which utilities are obliged to buy, averaged PLN0.249 (US$0.772) per megawatt hour last month.

Switzerland
Swiss energy provider Energie de Sion-Région (ESR) has launched a residential rooftop leasing programme for PV installations in the Swiss canton of Valais.

Customers will be charged a monthly rate of CHF2.90 (US$3.11) per meter square with a surcharge of CHF14.50 (US$15.56), with which it would be possible to cover at least 20% of an average household's energy bill, states ESR.

Turkey
At the beginning of 2011, the Turkish Parliament passed a Renewable Energy Legislation with new guidelines for FiTs. The FiT is currently US$0.133/kWh for owners commissioning a PV system before the end of 2015. If components meet the domestic content criteria, the tariff will increase by up to US$0.067. FiTs apply to all types of PV installations, but large PV power plants will receive subsidies up to a maximum size of 600MWp.

The Turkish government has set a goal to increase renewable energy to 30% of total energy generation by 2023.

Americas

Canada
Feed-in tariffs in Ontario were set in 2009 but have since been reduced in various steps by between 21 and 32%. The rate currently sits at around US$0.539 for roof-top installations between 100kW to 500kW. Ground-mounted installations under 500kW have a FiT of US$0.388.

Furthermore, the FiT scheme has a number of special rules, ranging from eligibility criteria, which limit the installation of ground-mounted PV systems on high-yield agricultural land to domestic content requirements and additional "price adders" for Aboriginal and community-based projects.

Ecuador
The electricity authority of Ecuador adopted a system of feed-in tariffs for the development of renewable energy on April 14, 2011. The regulations cover both continental Ecuador and the Galápagos Islands. Solar PV has been offered a rate of US$0.38 for 15 years.

US – Vermont
Vermont's Energy Act is an attempt to make solar PV more affordable. The state is also encouraging utility-scale projects with incentives like the Standard Offer Program". The FiT currently stands at US$0.25.

Africa & Middle East

Iran
The country aims to produce 5,000MW of electricity from renewable energy resources, which would account for approximately 3% of Iran's overall needs. Iran's renewable energy programme, launched in 2008, offers US$0.081/kWh to all renewables.

Uganda
Uganda's solar market has experienced steady growth and has currently approximately 1.1MW of installed PV capacity, with over 30 companies operating in the PV market. The PV market has been encouraged by government projects and donor support within the institutional (especially rural) sector and solar home systems. Solar water heating is still in its infancy.

Opportunities within the PV sector are underlined by an ambitious target by the Government to supply 61% from a current 4% of total consumed energy from renewable sources by 2017. Solar will be a component but a target has not been specified. The greatest potential is identified in the segment of solar home systems.

The Rural Electrification Agency publishes subsidies and targeted approaches to encourage PV implementation, and has worked with the private sector, in co-operation with the World Bank, through the Energy for Rural Transformation Initiative for cost-sharing and market development.

Compiled by Nilima Choudhury
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News

Deconstructing solar photovoltaic energy: Part 1

Antonio Alvarez & **Elisa Yoo**, Acero Capital, Menlo Park, California, USA

ABSTRACT
The PV industry is currently going through a turbulent period. By deconstructing the PV market and its cost structure into logical components, the aim of this two-part paper is to bring some clarity to critical issues facing the industry. The first part will discuss how PV compares to other energy sources for generating electricity. The second part, which will appear in the next edition of *Photovoltaics International*, will take a look at investments in technology that will be required to drive down the cost of PV-generated electricity.

Introduction

This paper begins with a basic review of electricity generation and supply and will lead up to a discussion of the global capital investment required to enable 15% of the world's electricity to be generated by photovoltaic (PV) energy by 2035 – and whether that makes financial sense. To link these two points together, a framework for understanding how PV compares to other energy sources for generating electricity is first constructed. The cost of electricity, along with the consequential cost points that PV-generated electricity must achieve to be economically competitive, is then reviewed. Another section will cover the limitations to PV market growth that are imposed by the way in which existing electrical grids are operated.

To bridge the gap between how electricity consumers and PV component manufacturers measure cost, a simple levelized cost of energy (LCOE) to dollars per watt translator is presented. This lays the foundation for a cost breakdown of the PV energy supply chain from cell manufacturing to system installation. In the final sections the PV market evolution is reviewed. The likelihood of 15% of the world's electricity being generated by PV energy is discussed from a financial perspective, and industry profitability requirements are proposed.

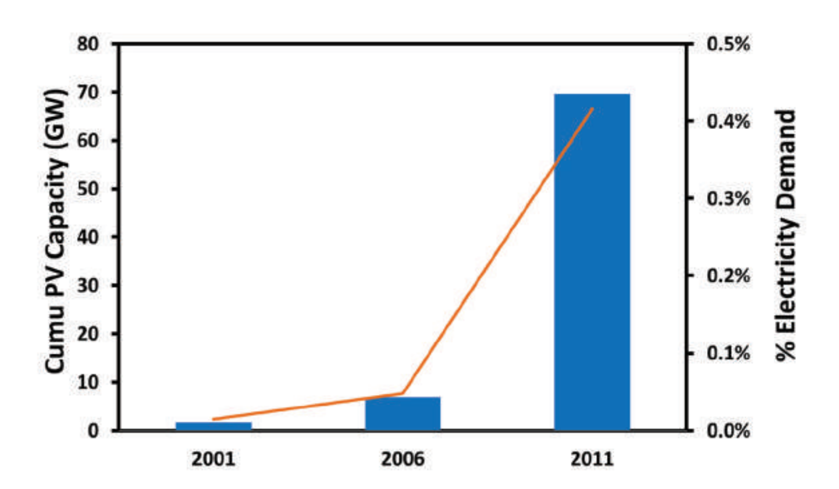


Figure 1. Worldwide electricity produced by PV energy.

Source: EPIA, BP Statistical Review, Acero calculations

"Although the PV market has grown impressively, it still produces only a little over 0.4% of the world's electricity."

The PV market in perspective

As is typical of most nascent markets, especially those in the technology sector, the PV market has experienced a great deal of upheaval and even chaos during its formative years. This has been clearly demonstrated over the past two to three years, as the pricing dynamics, investment outlook and regulatory incentives have been in constant flux. The net result is an over-capacity situation that has led to bankruptcies, distressed acquisitions, capacity slowdowns, factory shutdowns and a precipitous drop in the market capitalization of public PV companies. While certainly cause for concern, this current state needs to be kept in perspective. Although the PV market has grown impressively – by a factor of 10 in the past five years (and a factor of 40 in the past 10 years) – it still produces only a little over 0.4% of the world's electricity [1,2] (Fig. 1).

It follows that the PV market is just getting started and, despite its recent setbacks, will continue to grow rapidly. Possibly the most pertinent question at this time is how to grow the industry in a profitable manner. To answer this question it is necessary to look at: 1) energy sources used to produce the world's electricity; 2)

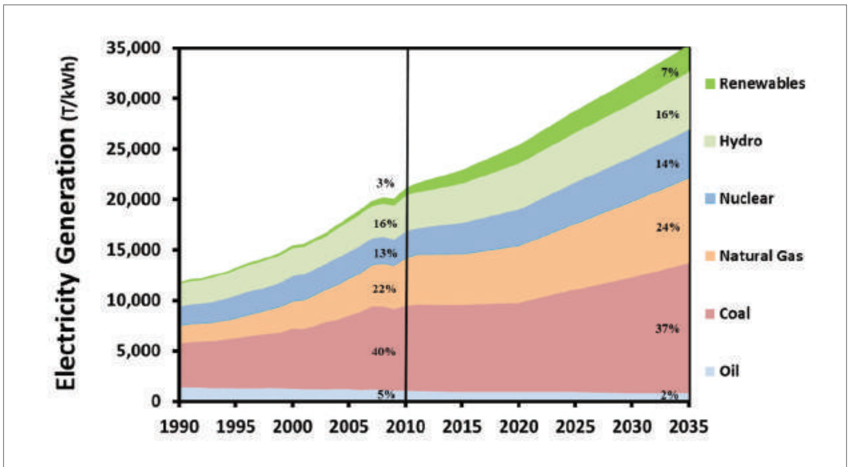


Figure 2. Forecast global energy sources for electricity generation.

Source: EIA, IEA, BP

price points resulting from these different energy sources; and 3) prices at which electricity is bought.

Deconstructing the energy sources for generating electricity

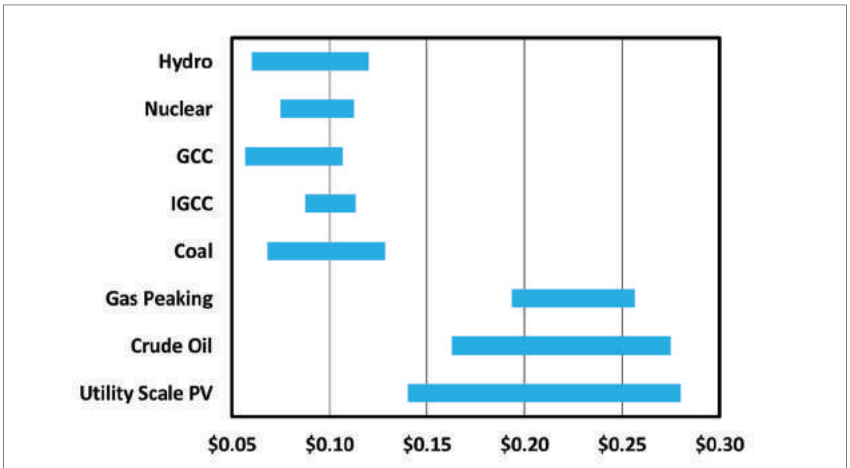
Over 60% of the world's electricity today is generated from coal and natural gas (Fig. 2), while nuclear energy generates approximately 13% [2,3,4]. Hydropower is by far the largest renewable energy source, contributing 16% to global electricity generation and making up ~80% of total renewable energy [4]. The PV portion is ~12% of non-hydroelectric renewables, or, as noted earlier, ~0.4% of the world's total electricity generation. Looking forward, the expectation is that, while renewables – including PV – will be the fastest growing segment of the overall electricity generation market, they will still constitute under 10% by 2035 [2].

Deconstructing the cost of electricity

The use of different energy sources results in electricity with a range of price points (Fig. 3). Nonetheless, the energy sources that make up the bulk of the electricity market in Fig. 2 – coal, natural gas, hydroelectric and nuclear – are all able to produce electricity at US$0.10/kWh or less in the USA [5]. Utility-scale PV in the USA today is only competitive with electricity generated from crude oil, which accounts for ~1% of electricity production (~5% worldwide), or with gas-peaking generators, which are only used a fraction of the time. The cost for unsubsidized residual PV installations is even higher – ranging from US$0.28/kWh to over US$0.50/kWh. Fortunately, there is no single price at which electricity is consumed (Fig. 4(a)) and therefore PV-generated electricity does not need to sell for US$0.05/kWh to US$0.10/kWh before it becomes competitive with other sources (conventional or renewable) of electricity.

> "The energy sources that make up the bulk of the electricity market are all able to produce electricity at US$0.10/kWh or less in the USA."

Retail electricity prices refer to the prices paid by consumers. These prices can be compensated by savings generated from the electricity production of residential PV systems. *Wholesale electricity prices* refer to the prices that utilities pay or receive.



Source: Lazard (June 2011), EIA (September 2011)

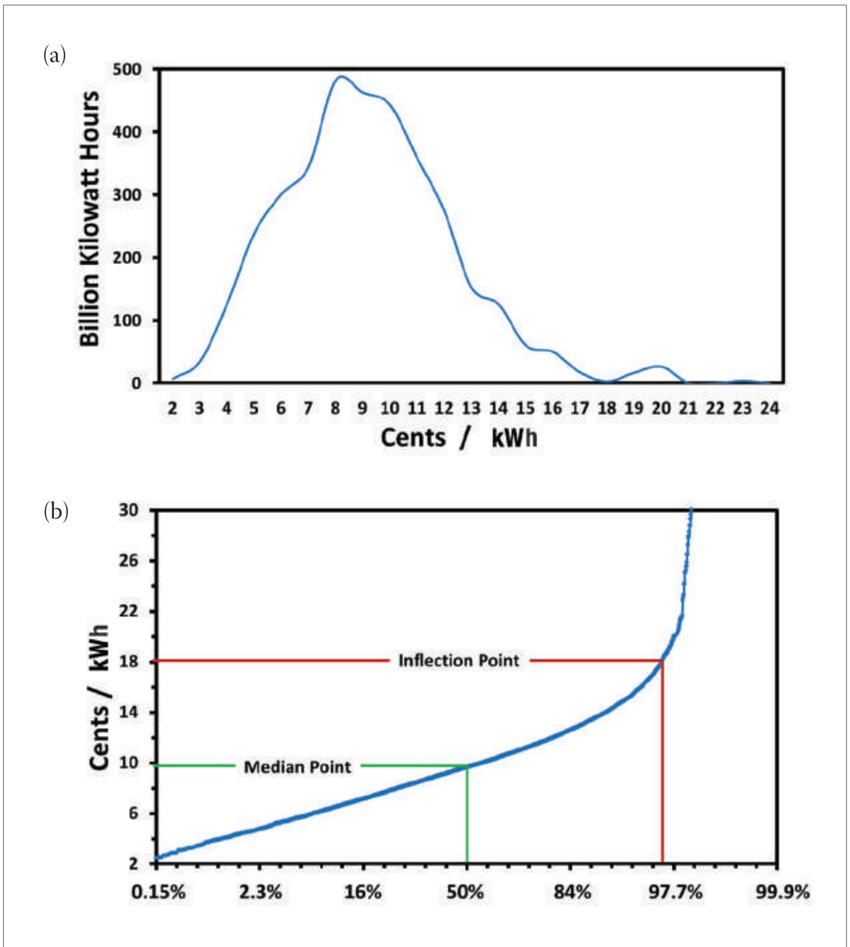
Figure 3. Cost of electricity produced from different energy sources (GCC = gas combined cycle, IGCC = integrated gasification combined cycle). Note: carbon capture is not assumed.

Market Watch

In addition, there is not a one-to-one correspondence between the price at which electricity is bought and sold, and the cost of producing that same electricity at a given time. Setting aside the impact of wholesale vs. retail electricity markets, the amount of electricity purchased depends not just on the source of electricity, but also on:

1. Location – USA (Texas vs. California vs. Hawaii) vs. France vs. Korea vs. China.
2. Type of customer – residential, commercial, industrial.
3. Time of day – the cost varies by time of day even though not all customers see time-of-day charges.
4. Regulated pricing, tariffs, etc.
5. Geopolitical factors, national security, etc.

This dependence is illustrated in Fig. 4(a), which shows the amount of US



Source: EIA November 2011, After Keiser Analytics

Source: EIA November 2011

Figure 4. (a) US electricity consumed in 2010 vs. prices; (b) probability plot of the US electricity prices in 2010 from Fig. 4(a).

electricity consumed at different price points [6,7]. Transforming the data in Fig 4(a) into a probability plot provides insight into the costs that PV needs to achieve in order to provide electricity at a competitive rate (Fig 4(b)). While in practice the analysis would need to be done on a location-specific basis, the aggregate US data is used in this work as a proxy for the industry.

When PV suppliers can sell electricity (profitably and without subsidies) at ~US$0.18/kWh, an inflection or tipping point occurs (Fig. 4(b)). As the industry continues to reduce costs beyond this point, electricity generated by PV becomes increasingly economical and is therefore pulled into the electrical grid on a more ***sustainable*** basis. While 2011 US unsubsidized installed residential PV costs were, for the most part, off this chart, the recent fall in PV module and balance of system (BOS) costs has resulted in the median utility PV unsubsidized installation cost approaching the US$0.18/kWh inflection point [8].

The other critical point, often called 'grid parity,' is the median of the distribution, or ~US$0.10/kWh, as shown in Fig. 4(b). When the PV industry can achieve this metric, it becomes cost-competitive with half of the electricity produced by the aggregation of power sources. But cost is not the only criterion that determines market share in the electricity market. As will be discussed in the next section, an important criterion pertinent to the PV industry is energy source reliability or dispatchability with respect to the electrical grid.

Deconstructing the electrical grid

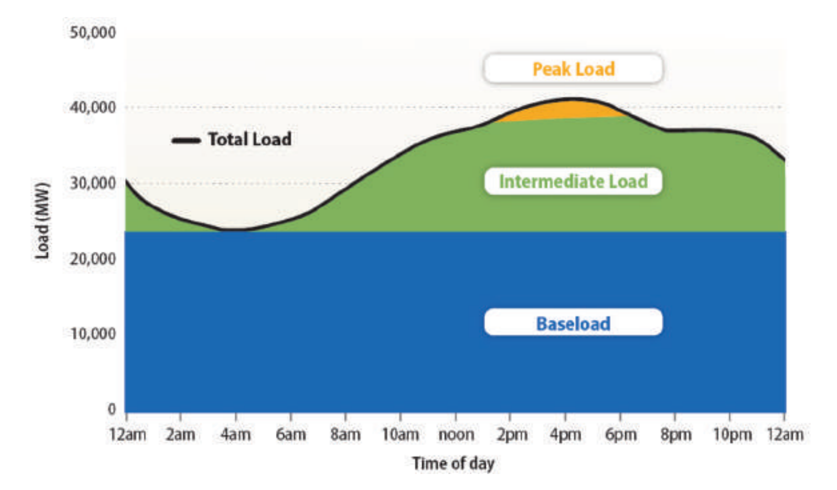
The way electrical grids are constructed and operated today dictates a requirement for power sources with different characteristics. Electricity demand fluctuates over the course of a day, throughout the week and seasonally [9] (Fig. 5). In response to fluctuating demands the electric grid has evolved to consist of three distinct supply/load segments: base, intermediate and peak [10].

The suitability of a power source in addressing the load demands in each of the three different categories depends on its specific characteristics [11,12]. Base-load power plants, for example, must generate dependable power to consistently meet demand around the clock in an efficient, reliable and inexpensive manner regardless of demand fluctuations. Base-load plants designed to meet these characteristics are typically large, run continuously at full capacity (except for major preventive maintenance), and are not very efficient in responding to rapidly fluctuating loads. In typical grid systems, base-load power is 40–50% of the maximum load in order to insure that the plant runs continuously.

Intermediate-load power plants are designed to be responsive to fluctuations in load and are often known as 'load-following' power plants. They are smaller than baseload plants, operate 30–60% of the time and are therefore more expensive to run.

Finally, peak-load, or 'peaker,' plants are designed to be highly responsive to changes in electrical demand. They can be started up and shut down quickly and can vary the quantity of electrical output by the minute. Since peak-load plants are only required for peak demand (in the USA this typically occurs during hot summer afternoons), they tend to have smaller output and only operate 10–15% of the time. As a consequence they are also the most expensive to operate. Table 1 gives a summary of the different generating plants. The electrical grid structure is one of the reasons why different types of power plants and sources have been developed over time and is also one of the reasons for the broad range of electricity cost/pricing.

Renewables such as wind and solar do not fit neatly into this simple construct. Before the advent of renewables, increasing demand for power (up to a point) was satisfied by generating plants increasing their output, typically by consuming more fuel. In a system without any renewables, generating units are put on-line (i.e. dispatched) in order of lowest variable cost [11]. With renewables, however, the procedure is reversed. Most renewable



Source: NREL, March 2010

Figure 5. Electricity demand load over a 24-hour period.

	% of annual max load target	% of annual electricity provided	Type of plant	Ability to cycle/ demand response	Capacity factor	Size	Operating time	Typical cost ($/kWh)
Base	40–50%	50–60%	· Coal · Natural gas · Nuclear · Large hydro	Poor	70%+	Large: 500MW–1GW+	· Almost always on (except pm)	Low: 0.06 – 0.10
Intermediate	30–50%	20–40%	· Combined cycle CT · Steam turbine · Hydropower	Acceptable	35–55%	Medium: 200MW+ typical	· Follow demand during the day · On 30–60% of the time	Medium: 0.08–0.12
Peaking	Balance	5–10%	· Combustion turbine (CT) · Small hydro	Best	25%-	Small: < 50MW typical	· Only on very hot summer days · On 10–15% of the time	High: > 0.15

Source: Acero Capital

Table 1. General characteristics of electricity generation plants.

Market Watch

generating plants, and PV plants in particular, ramp up and down of their own accord, and grid operators must adjust to accommodate their outputs. In other words, grid operators need to use the power supplied by PV plants when available and then balance the grid system by reducing output from an existing conventional generating plant. Ideally, within a given interconnected grid, a PV plant's electricity would displace the output of the conventional plant with the highest variable cost [13–15]. Some advocates of renewable energy characterize this existing grid makeup as outdated and claim that the onset of greater grid intelligence will make the concept of base-load power obsolete [16,17]. For better or worse, however, given the huge infrastructure in place, this change, if it happens at all, will take place over several decades.

To get a feeling for an electrical grid's complexity, consider the US national electric power system. It consists of three independently synchronized grids (Eastern, Western and Texas) linked by a small number of relatively low-capacity lines. Within these areas are 107 balancing authorities in eight regions, coordinated by the North America Electric Reliability Corporation (NERC). The authorities are responsible for balancing the supply and demand for power in real time within specified areas. Combined, the three independent grids serve over 143 million residential, commercial and industrial customers through more than six million miles of transmission and distribution lines owned by more than 3000 diverse investor-owned, government-owned and cooperative enterprises. At the generation level, investor-owned utilities and independent power producers each account for ~42% of the electricity generation (84% total). Cooperatives and federal systems account for an additional ~4% each (8% total), while publicly owned systems organized at the state or municipal level account for the remaining 8% [18]. This system, which took decades to put in place, will not change overnight.

Even setting aside transmission issues, it follows that for the near term there are challenges in integrating PV generation into a conventional electric grid. In addition to the limited dispatchability of PV-generated electricity, there is the issue of intermittency or variability/uncertainty associated with dependencies on the weather and cloud coverage. For up to 10% of PV generation grid penetration, the system load during high demand is reduced while having little or no appreciable impact on the minimum (base) load. As PV penetration reaches 10–15%, greater steps need to be taken, but still the intermittency problem can be managed with a combination of better planning, increased flexibility of conventional generating plants, greater cross-region grid integration, increased operating reserves, mixed-mode generation plants (i.e. combinations of PV, wind and IGCC co-located or integrated) and some limited degree of storage. Above 20% PV penetration, it becomes increasingly difficult to maintain system reliability. Even achieving 10 to 15% PV penetration comes at a cost: estimates of the additional cost burden range from 10 to 20%, increasing as the penetration of PV in the electric grid increases [14]. All solutions to the intermittency problem – be they storage, or maintaining back-up or redundant conventional power sources, or even adding additional grid intelligence – come at a cost.

So where does PV-generated electricity best fit into this grid structure? With respect to system planning, a key characteristic of PV's generation profile is its correlation with periods of high electricity demand. This has obvious benefits: the presence of PV as part of the grid implies that expensive peaker plants are not required to run as often or may even be taken off-line, which in turn lowers the overall system operating cost. On the other hand, this period of high electricity demand is also when the system is most vulnerable, so greater care needs to be taken in load management. (Note: as grid penetration increases, the midday summer demand peak will most likely be eliminated and a new demand peak – late afternoons or winter evenings – may prevail. If this comes to pass, additional PV will produce power at off-peak demand.)

Aside from serving to reduce the need for electricity from peaker plants, PV-generated electricity can also fill part of the role served by conventional intermediate power plants. Since these intermediate plants can respond to load fluctuations in a relatively efficient manner, a portion of the conventional intermediate power plant generation can also be reduced by integrating PV into the overall system planning, and it may be possible to reduce the percentage of load covered by baseload plants to 35%.

> "PV currently best fits into the grid for peaking and intermediate load applications."

In conclusion, PV currently best fits into the grid for peaking and intermediate load applications. The PV-served available market is therefore limited to approximately half of the total electricity generation required, but also does not force PV to compete directly with the lowest-cost power sources. From a practical perspective, in the absence of low-cost storage (not likely in the near term) and modest penetration by other renewable energy sources, the figure of 15 to 20% is a likely upper limit of PV grid penetration over the next 20–30 years. This, as will be shown later, is still an enormous market opportunity.

Translating LCOE to dollars per watt

Even though PV suppliers take into account the levelized cost of energy (LCOE = total lifecycle costs divided by total lifetime energy production) in their positioning and pricing strategies, the industry discourse and benchmarks are given in price (or cost) per watt (US$/W), i.e. the cost of energy generation. Electricity consumers on the other hand talk in terms of cents per kWh, i.e. the cost of power consumption. What is needed is a way of translating between the two.

The LCOE can be a relatively complex calculation [19], as it depends on:

1. Total life cycle costs:
   - Cost of the project/system
   - Amortization or financing costs (discount rate, loan duration, amount financed, etc.)
   - Operating and maintenance (O&M) costs
   - Residual system value
   - Tax rate

2. Total lifetime energy production:
   - Average daily insolation, i.e. the amount of sun the system receives
   - Energy harvest (panel efficiency, sensitivity to temperature and to low or diffused light, etc.)
   - System losses (inefficiencies, soiling, etc.) and downtime (inverter or other malfunction or failure point)
   - System degradation over time (guaranteed <1%/year for most PV systems and typically 0.2–0.5%)

By using a few simplifying assumptions, the cost per watt of PV installation is translated into the LCOE as shown in Fig. 6. Since irradiation is a major driver of the LCOE, three levels are shown: 1) 1100kWh/m^2/year (representative of Germany); 2) 1800kWh/m^2/year (representative of much of the USA and portions of Spain); and 3) 2400kWh/m^2/year (representative of the US southwest). The US$0.18/kWh inflection point previously noted corresponds to an installed PV price point of ~US$2.50/W (unsubsidized) at a nominal irradiation of 1800kWh/m^2/year (red star). Similarly, US$0.10/kWh (median point) corresponds to ~US$1.45/W (green star). These are key points to keep in mind. The three vertical dashed lines correspond to average US PV installation costs for residential (~US$5.90), non-residential

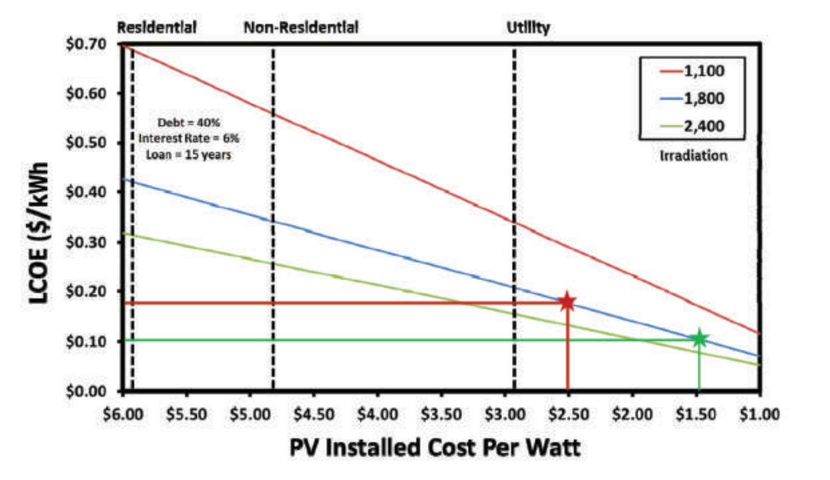
(~US$4.80) and utility-scale (~US$2.90) projects as of the first quarter of 2012 [8]. As noted previously, only utility-scale installations are approaching the US$0.18/kWh inflection point and then only at the highest levels of irradiation. As the industry drives towards profitability at US$0.18/kWh and subsequently at US$0.10/kWh, a large, sustainable and attractive PV electricity market will emerge. The question is, when will suppliers hit these cost points?

PV system installation costs are commonly divided into two categories: BOS and module. But, to better illustrate the critical cost-driving components of the PV value chain, installation costs have been divided into three categories: BOS, module and cell. While cost extrapolations are often done at the installation or module level it should be obvious that learning rates associated with each of these three categories will be fundamentally different and it is critical to differentiate between them (Fig. 7). Comparisons with Moore's law for integrated circuits, which are often done, are not applicable here. The main reason is that, in all three categories, raw materials make up 50–70% of the total cost and they do not 'scale' down. Nevertheless, there are volume learning rates associated with all three categories, and it is possible to ascertain the relative learning rate for each category by breaking it down into major components:

1. BOS: power conditioning/inverter, structural components (racking material, hardware, wiring, etc.) and items associated with the actual installation such as project management, permitting, site development, labour, etc.
2. Module: materials (~70%: EVA, backsheet, glass, frame, cell interconnect, glue), junction box, depreciation, utilities, labour, etc.
3. Cell:
   (a) Substrate: polysilicon (~50% in Si cells), glass, metal film, processing, depreciation, labour, etc.
   (b) Wafer: materials (~60% in Si cells: slurry, wire saw), depreciation, labour, etc.
   (c) Cell conversion: raw materials (~55%: silver paste, screen, process materials, etc.), processing, depreciation, labour, etc.

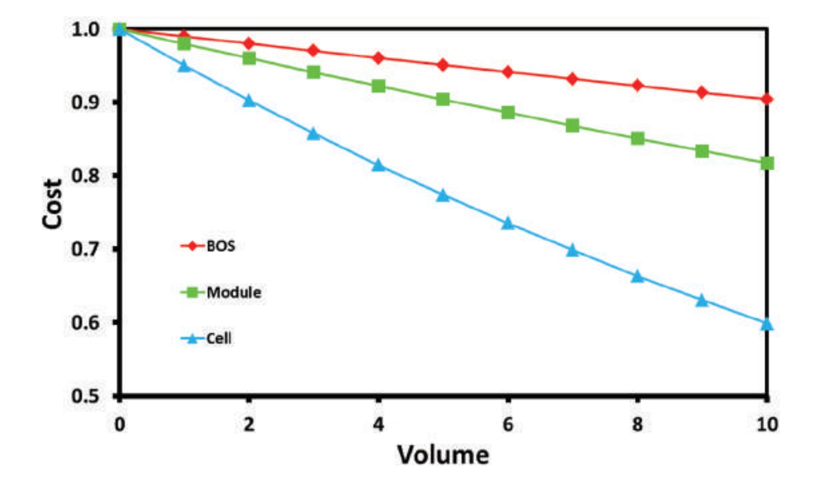
Intuitively, BOS costs – especially at the residential or small commercial level – would be expected to have the lowest learning rate. Installation tends to be relatively labour-intensive, extremely site specific and highly dependent on factors such as commodity price fluctuations in steel, copper and aluminium. Only the inverter is subject to a reasonable learning rate. And, since the inverter is basically a power component, even it does not lend itself to the same cost-reduction learning rates associated with digital technology.

Materials, including the cost of cells, make up the largest portion of module costs. Owing to its 'economic' immaturity relative to other material components, the cell has the highest potential for cost reduction. For a contrasting example, consider the front glass used in module construction. Glass is a fairly mature technology – it is not going to have the 30%/year cost-reduction learning rate that has characterized recent module cost reductions. Unless it is eliminated completely, the same can be said for the aluminium frame. It is not obvious that



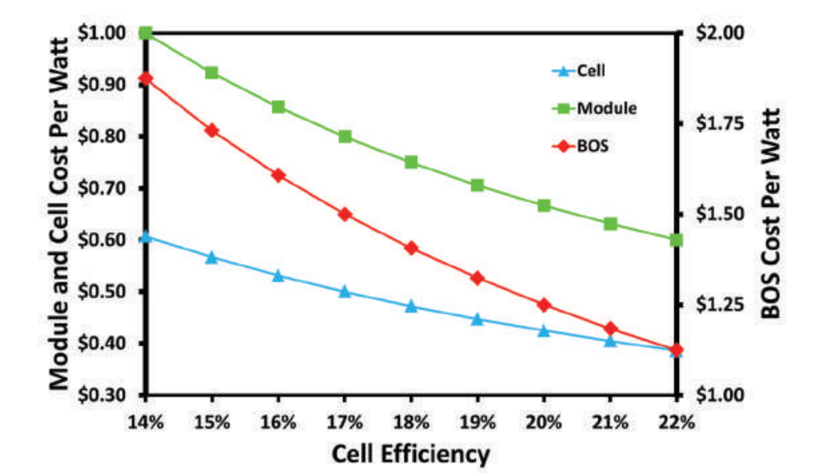
Source: Acero Capital (after Keiser Analytics)

Figure 6. LCOE (US$/kWh) vs. installed price (US$/W) (red star = US electricity pricing inflection point; green star = US electricity pricing median point).



Source: Acero Capital

Figure 7. Relative learning rates for PV component absolute costs.



Source: Acero Capital

Figure 8. PV component cost in US$/W vs. cell efficiency at fixed absolute cost.

labour is going to get much cheaper. It follows that the portion of the PV value chain that can exhibit the highest learning rate is the cell.

> "The portion of the PV value chain that can exhibit the highest learning rate is the cell."

Cell innovation drives costs in two ways: first, through normal component cost reduction characterized by production efficiency increases and economies of scale; second, through increased efficiency characterized by continuous technology improvements. Since PV costs are normalized by watts generated, any increase in cell efficiency gets leveraged through the value chain, i.e. BOS and module costs. This impact can be quantified by calculating the cost per watt for a cell, module and BOS assuming a fixed dollar cost for each component at nominal cell efficiency (17% in this example), and then calculating the cost per watt as the cell efficiency varies (Fig. 8). The impact of cell efficiency on PV component dollar per watt cost ranges from 8% at lower efficiencies to 5% at higher efficiencies for each absolute per cent improvement in cell efficiency. In a world where profits are measured in single-digit percentages, this is a significant impact.

Conclusion

Accounting for just 0.4% of the world's electricity generation in 2011, the PV power generation market is just getting started. The industry is exhibiting the fits, starts and growth pains typical of any nascent industry. Subsidies have up until now driven the PV market and enabled a rapid reduction in PV cost, especially in the last three years as the industry achieved critical mass: ~$100 billion total available market (TAM). While electricity produced through PV is still, in general, not cost-effective compared to conventional sources of electrical power generation, its cost is approaching a tipping point.

One critical question is what new disruptive technologies will be required (and when) in each of the three categories – BOS, module and cell – to maintain the necessary cost learning rates in order to continue to drive the cost of PV-generated electricity down from today's US$0.20–US$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 in monolithic and frameless methods for (automated) module construction, etc. Some of these technologies will become mainstream – most will not. In an attempt to answer the question above, each technology will be examined separately in detail in the second part of this article, which will appear in the next edition of *Photovoltaics International*. Beginning with a cost breakdown of the PV energy supply chain from system installation to cell manufacturing, Part 2 will review PV market evolution and will discuss, from a global financial perspective, the likelihood of 15% of the world's electricity being generated by PV energy, as well as industry profitability requirements.

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US solar industry rolls up its sleeve for a new dawn

Will Obama's second term mean a fresh start for US solar?

Now the election bunting has been taken down, the real work begins in preparation for Barack Obama's second term as US President. Renewable energy companies across the country breathed a sigh of relief. But does his landmark victory mark a new dawn for solar?

Rhone Resch, Chief Executive of the Solar Energy Industries Association (SEIA), gave prospects of another stint for Obama in the White House a warm welcome. "Since President Obama took office, the amount of solar powering homes, businesses, and military bases has grown by 400% – from 1,100MW in 2008 to more than 5,700MW today," he said. "As we recover from the recession, America needs plentiful and diverse energy resources, including solar, to power our economy."

We're unlikely to see anything substantial until after Obama's inauguration. Some are hoping for progress with the appointment of Democrat Oregon Senator, Ron Wyden, to Chairman of the Senate Committee on Energy and Natural Resources. But as the fevered discussions about a national carbon tax have shown, now is the time to write your wish-list.

Obama took quite a lot of stick in his first term for pinning job growth to his economic stimulus. And although organisations like the SEIA will point to an industry that employs 119,000 Americans at 5,600 companies, the Obama administration's numbers fell short of expectations.

But that might change, at least at the state level, with the likes of California switching focus to distributed generation (DG). Governor Jerry Brown has an ambitious target of 12GW of DG by 2020 and describes the state's 33% Renewable Portfolio Standard as a floor, not a ceiling.

Dustin Mulvaney, Assistant Professor of Sustainable Energy Resources at San Jose State University, is no advocate of utility-scale solar, which has stolen the megawatt limelight in recent years. DG yields more jobs per megawatt than utility scale, he said.

"The advantages of DG far outswamp the advantages of high insolation desert installations. A lot of the project developers I've been speaking to are going a bit smaller with their next round of projects. It seems there is a lot of opportunity there and particularly as we start to develop more local DG that's really where all the job growth is."

However, the utility sector is here to stay and will continue to take the largest market share for some time to come. But its profile will change from mega-projects stranded from population centres to large and mid-size projects closer to load.

Sheldon Kimber is the Chief Operating Officer at Recurrent Energy, which is the primary solar developer for Sharp. The San Francisco-based company focuses on projects in the 20MW range and may well have hit a sweet spot in project size, with contracts signed for 600MW.

Sheldon said the idea of partisanship in solar was "silly". "I don't understand why renewable energy is a liberal thing and not a conservative thing," he said.

"It's only that way because the way in which some advocates of renewable energy have gone about advocating has turned it into a partisan game. From what is being said publicly Obama's team has spent more time focused on renewable energy and would be the clear choice for furthering renewable energy in this country."

Good policy at state and federal level, along with an extension of the Investment Tax Credit beyond 2016 would now be extremely helpful for the solar industry going forward, he said. But upstream vendors also need to do their part, Kimber added.

"The market price right now is what it takes to do solar and as the upstream business consolidates and comes together it needs to continue to find ways to do things at least cost.

"[Some people think] we can make a smaller cottage industry where we take premium prices and go after premium markets — that can't happen. The only path forward is to realise that there's tremendous scale and opportunity but we've got to remain at these really low prices and become even more competitive.

"They are very difficult decisions right now given the fiscal situations, but the willpower to push solar forward is really what we're going to rely on in the next two years. The biggest opportunity is just the scale of the market. Everyone in solar needs to see themselves as a member of the electric power industry. That opportunity is massive."

This column is a revised version of a blog that originally appeared on PV-Tech.org.

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