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THE MAGAZINE FOR SOLAR POWER
By Renewable Energy World Network

Addressing PV durability and reliability p.10

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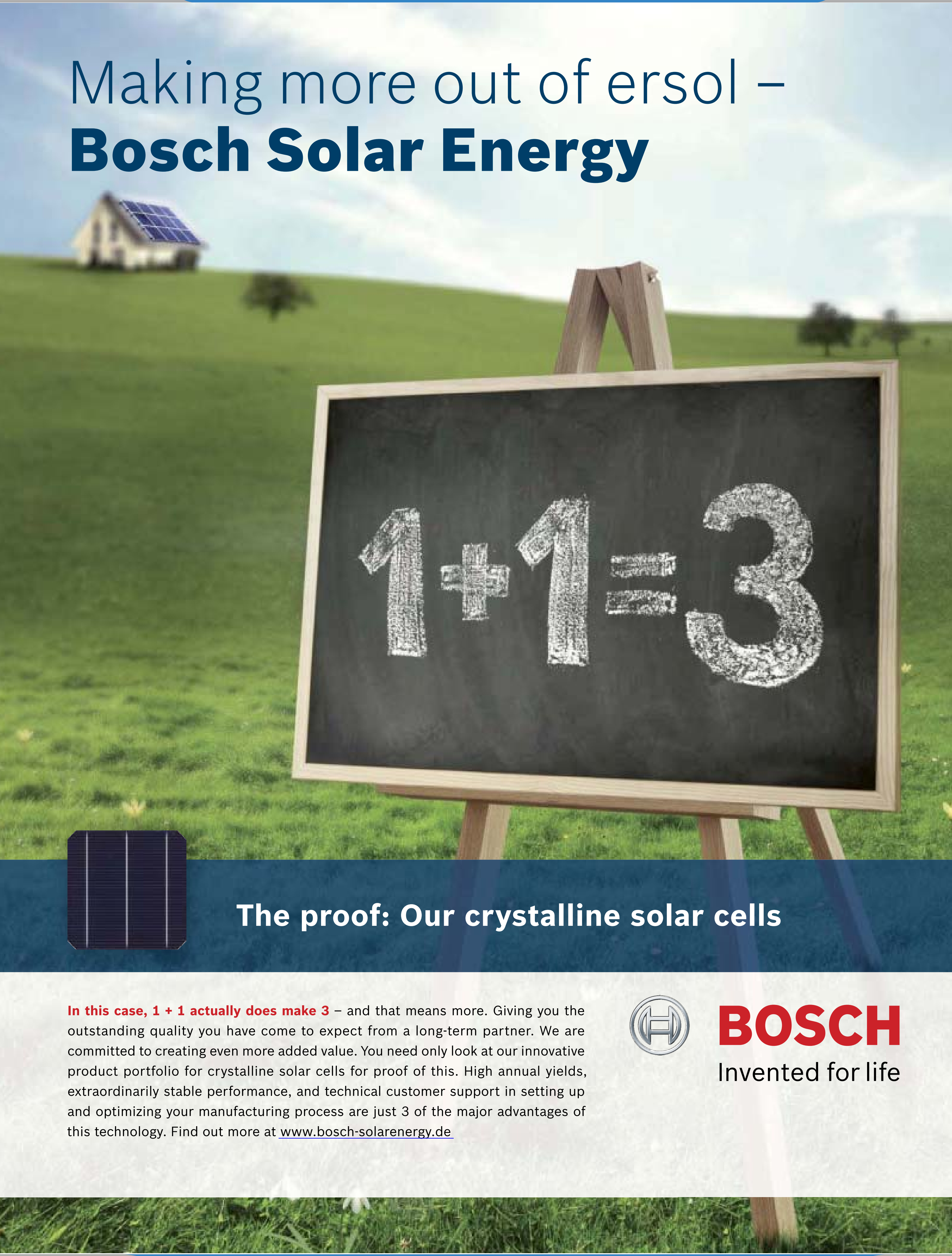
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WORLD

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Columns

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Features

On the cover
An improved testing methodology that more closely simulates the real environment can be a valuable tool. *(Source: Atlas Material Testing LLTechnology)*

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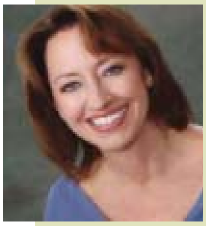
Online

Web Exclusives

Germany and California: Changes leave the devil in the details

Analysis of changes in Germany's FiT and possible cap, and California's promising yet complex net excess and FiT programs, shows that the devil may well be in the pesky details, and could lead to more than one down year for the solar industry, explains Navigant Consulting's Paula Mints.

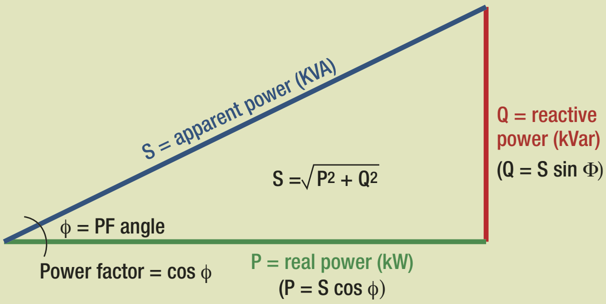


Cogeneration and hydrogen production for solar-grade polysilicon

Fluor's Louie M. De los Santos explains the benefits of integrating combined heat and power (CHP) and hydrogen generation with large-scale polysilicon manufacturing, including reduced operational costs and greenhouse emissions.

How PV grid-tie inverters can zap utility power factor

Large grid-tie inverter systems are becoming more prevalent, and export energy credits from feed-in-tariffs help defray the large capital expenditure—but a sub-par power factor could bring penalty charges from your utility. Gerritt Lee explains the problem and offers a solution.



Opportunities and risks in the Italian PV markets

With the introduction of an amended feed-in tariff rule, Italy has succeeded in engendering a huge surge in PV activity—but there are still a number of potential pitfalls, as explained by Dietmar Zischg and Alessandro Antonioli of CMS Adonnino Ascoli & Cavasola Scamoni.

EU PVSEC highlights new equipment landscape for solar cell production

This year's EU PVSEC exhibition was notable for the plethora of new production tools and processes for next-generation crystalline-silicon production lines, as suppliers respond to cell manufacturers' prioritization of high-efficiency cell concepts. It's a great example of how market dynamics drive technology innovation, especially when supply exceeds demand by a considerable margin, observes Coherent's Finlay Colville.

Renewable companies see advantages in auto industry's pain

The recent deal to revamp an idle Ford assembly plant for thin-film solar PV manufacturing is one of several examples of clean-tech companies benefitting from the recession and opening factories in hard-hit regions, writes Jennifer Kho for *PVWorld* partner RenewableEnergyWorld.com.

Events

Featured Event

PV Industry Symposium at SEMICON Japan

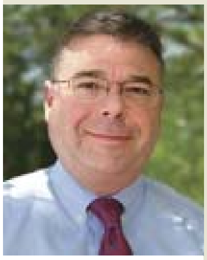
December 2
Chiba, Japan
www.semiconjapan.org

Analysts will offer insights into markets and R&D strategies in Japan, North America, Europe, and developing countries in Asia. Also examined will be trends in PV technology, and updates on the latest R&D from leading suppliers of cells and modules, equipment, and materials. Participants include AIST, Mitsubishi Electric, TEL, and Tsukuba Research Center.

Editorial

$8 billion in Smart Grid Investment: The PV part

Speaking at Florida Power and Light's DeSoto Next Generation Solar Energy Center in October, President Barack Obama announced the largest single energy grid modernization investment in U.S. history: $3.4 billion in Smart Grid Investment Grant awards, which will be matched by industry funding for a total public-private investment worth over $8 billion. One hundred private companies, utilities, manufacturers, cities and other partners received awards.



Pete Singer
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The idea behind this is that it will promote energy-saving choices for consumers, increase efficiency, and foster the growth of renewable energy sources like wind and solar. It's also designed to make the grid—which Carol Browner, assistant to the president for energy and climate change, called "antiquated" and "dilapidated"—more reliable, reducing power outages that cost American consumers $150 billion a year.

Part of the investment will be that install of more than 850 sensors—called 'phasor measurement units'—that will cover 100 percent of the U.S. electric grid, and make it possible for grid operators to better monitor grid conditions and prevent minor disturbances in the electrical system from cascading into local or regional power outages or blackouts. Of key importance to the PV community: this monitoring ability will also help the grid to incorporate large blocks of intermittent renewable energy, like wind and solar power, to take advantage of clean energy resources when they are available and make adjustments when they're not.

What could use more attention at the national level is net metering, which allows for the flow of electricity both to and from the customer – typically through a single, bi-directional meter. With net metering, during times when a customer's generation exceeds the customer's use, electricity from the customer flows back to the grid, offsetting electricity consumed by the customer at a different time. In effect, the customer uses excess generation to offset electricity that the customer otherwise would have to purchase at the utility's full retail rate. Net metering is offered in more than 35 states, and required by law in most states, but some of these laws only apply to investor-owned utilities, not to municipal utilities or electric cooperatives (see www.dsireusa.org for more info).

$8B is a great start, but there's a lot more to be done.

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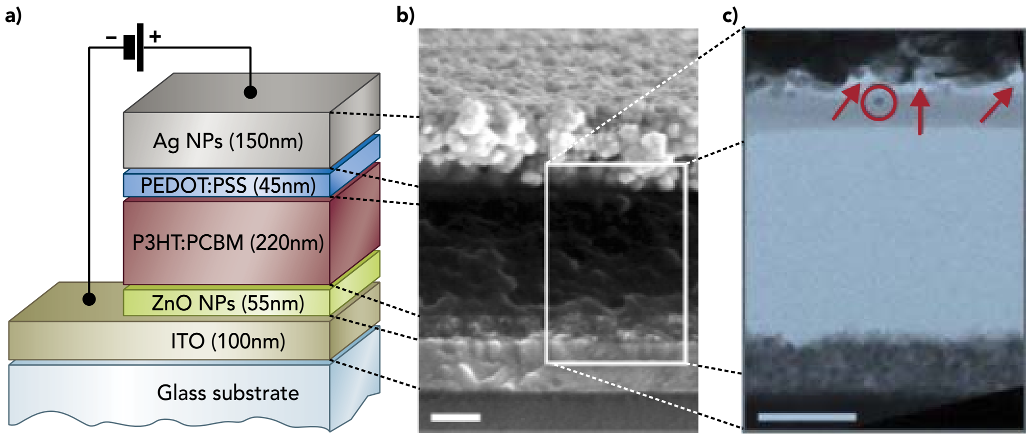
news

IMEC's Poortmans: Organic PC more than "niche"

IMEC recently demonstrated a fully solution-processes organic solar cell with a spray-coated active layer and metal top contact spray-coated on top, with power conversion efficiency (>3%) comparable to cells made with a spin-coated organic layer and vacuum-evaporated top contact metal. For the metal top contact, IMEC spray-coated a solution with silver nanoparticles at 150°C— a temperature compatible with processing on flexible substrates. The challenges are to do this process without dissolving the underlying layer and without damaging it by the temperature needed to sinter the silver nanoparticles, but IMEC says that it demonstrated that spray-coating greatly reduces the damage to underlying layers compared to other techniques.

In an interview during IMEC's annual media event in Leuven, Belgium, (Oct. 5-6), Jef Poortmans, program director for photovoltaics, listed several main reasons IMEC has chosen to work on organic solar cells: sufficient efficiency potential for the technology, sustainable technology, and synergy with other activities at IMEC. The world record efficiency for organic PV (6.7%) is not the technology's limit, he believes. "If you think about the specific properties of organic materials, they have a relatively narrow absorption band," he said. This property means that these materials can be used in an organic multijunction structure, or stack of layers, each of them absorbing a different part of the spectrum. "So, you would expect much higher efficiencies with this sort of approach—you'd be absorbing each part of the spectrum with the applicable organic material."

In such a multijunction organic structure, for example, light would come into the first layer of material that would absorb the high-energy photons; the light not absorbed in the first cell goes to the second, and so forth. With this sort of structure an efficiency of 15% is conceivable, Poortmans thinks. Much lower manufacturing costs would be incurred, however, than with other types of cell technologies. Organic solar cells can be deposited in non-vacuum conditions using simple techniques, such as printing, "so it could be a very low cost technique where you could have bottom up patterning—you can immediately print a thin layer with a pattern," said Poortmans.



The polymer solar cell with a spray coated Ag top contact: (a) schematic build-up, (b) SEM, and (c) FIB/TEM cross-sections. (Source: IMEC)

Admittedly, organic PV cells initially will be limited to niche markets, Poortmans acknowledges, "but once we improve efficiency and stability simultaneously, we could have a situation where 10-15 years from now, we could use organic PV cells as an option in grid-connected high-power applications."

The payoff for developing organic PV cells is in its promise of low-cost production and high throughput; however, this can only become true if all the layers of the cells can be deposited by solution-based, in-line compatible methods, according to IMEC. Its research shows that spray-coating is a suitable deposition technique, and that it can be used to deposit all layers, including the metal top contact. Spray-coating is a high-rate, large-area deposition technique that ensures an ideal coating on a variety of surfaces with different morphologies and topographies. — *D.V.*

Innovalight draws the curtain (just a bit) on its Cougar c-Si tech

Homer Antoniadis, CTO and VP of engineering at Innovalight, discussed some details of the company's 18%-efficient "Cougar" technology with *PV World*—including that higher efficiencies have been obtained in the lab.

The company's core technology is a proprietary silicon ink and a process to fabricate high-efficiency crystalline silicon (c-Si) cells. A standard cell process makes a uniform emitter, he explained. "By inserting only one additional step using an industrial inkjet printer, we are able to enhance the overall efficiency of the solar cell." A pattern is introduced onto the surface of the incoming c-Si substrate using an ink printing/drying process coupled with a thermal process to enable activation. Higher n-type doping is achieved under the metal layers (high conductivity), and lighter doping is achieved everywhere else (lower conductivity). "The n-type doping pattern can easily be recognized by the cameras of the metallization tool via an auto-alignment capability without the need for fiducials," he added.

The Cougar cell architecture is key to improving the amount of absorbed photons that get utilized in the cell, Antoniadis noted. "You need to drop the resistivity under the metal and increase it between the metal contacts," he said. The lighter doping lowers recombination losses; therefore, with fewer dopant atoms, surface recombination velocity is improved and more charges are generated at the cell surface. "A standard cell has uniform doping throughout, which kills the photoresponse," he noted.

JA Solar plans to develop solar products using Innovalight's technology, with commercialization planned for sometime in 2010. — *D.V.*

Records fall at EU PVSEC

At this year's European Photovoltaic Solar Energy Conference (EU PVSEC), several firms showed off record improvements in conversion efficiency for a range of PV cell types, from single/multi-crystal and amorphous silicon to thin-film and multijunction/concentrated technology:

Sunovia and EPIR Technologies: Single- and two-junction CdTe-based solar cells with highest-ever open circuit voltages, beating previous marks by 45%.

IMEC: GaAs/Ge multijunction cell demo with potential >40% efficiency (using concentrated illumination).

Q-Cells AG: 15.9% conversion for its poly-Si solar cells.

Fraunhofer Institute for Solar Energy Systems (ISE): Prototype n-type silicon solar cells with conversion efficiency exceeding a record 23.4%; a bigger cell (12.5×12.5cm^2) "using much simpler process stages close to industry practice" reached 18.2% efficiency.

Suntech Power: A 16.53%-efficient multi-crystalline silicon cell, nearly a full point better than its previous record mark.

Oerlikon Solar: a-Si single-junction photovoltaic cells with >10% conversion efficiency, proven in a repeatable process. — *J.M.*

PV durability and reliability issues

ALLEN ZIELNIK, Atlas Material Testing Technology LLC, Chicago, IL USA

The photovoltaic industry needs PV modules that will perform for ~25 years or longer in the field, as well as a reliable means to determine that viability. These are necessary not only for product development and warranty considerations, but also in terms of risk to financial stakeholders and overall economic viability—not to mention key safety concerns.

While there are initial PV qualification tests, such as the IEC and UL requirements, among others, they are neither intended to, nor capable of, predicting long-term performance. As a result, there has been an evolution in the application of accelerated life testing (ALT) and accelerated environmental testing (AET) to the service life prediction (SLP) of PV modules and systems.

While no abbreviated test program can predict with 100% certainty that a module will properly perform in an environment for 25+ years, an improved methodology that more closely simulates the real environment, while still maintaining reasonable acceleration, can certainly be a valuable tool to assess the question of survivability.

25 years and beyond

To understand reliability, we must first define what we mean. For simplicity, we will say a PV module fails to provide service if its power output decreases by more than 20% after 30 years in its use environment. Also, "a high probability" means that 95% of the modules in the field will achieve this success [1]," or the like.

For most PV products, there are many additional concerns regarding what constitutes failure or unacceptable performance. Notably, safety after aging is a critical concern to protect life and property. There may also be critical aesthetic concerns, such as with BIPV products, which affect the viability (but not necessarily the power generation) of the product. If a module discolors in the Mojave Desert, no one may care, but if it discolors on a building façade, everyone may care (at least one BIPV producer is out of business due to cosmetic failure).

At the Department of Energy "Accelerated Aging Testing and Reliability in Photovoltaics Workshop II" held in 2008, Akira Terao [2] (Sunpower Corp.) pointed out that, even in the mature c-Si module arena, there are still many remaining reliability challenges, including:

- *25-year warranty.* This is still a barrier; how does a company prove 25-year life?
- *Ill-defined field conditions.* The same warranty must apply for all conditions for the same modules.
- *Harsh and varied outdoor conditions.*
- *Materials used near their limits;* how to accelerate the effects on material already being used near its limit.
- *Limited acceleration factors.* There are few available; industry must rely on long tests instead. Long test time can be a hindrance to market introduction.
- *Cumulative effects, positive feedback loops.* Challenging to determine and test for all interactions in the field.

The best approaches to reliability engineering include using the standard Weibull bathtub curve to determine the physics of failure for each mode.

According to John Wohlgemuth (BP Solar), "Today, BP Solar offers a 25-year warranty on most of its crystalline silicon PV modules...while the modules have to last for 25 years of outdoor exposure, we cannot wait 25 years to see how they perform... no BP/Solarex module has been in the field longer than ten years. Even the oldest 20-year warranty modules have only been in the field 15 years."

Wohlgemuth adds, "Examples of accelerated stress tests of use for PV include:

- Thermal cycling;
- Humidity-freeze;
- Damp heat;
- Mechanical load both static and dynamic, and

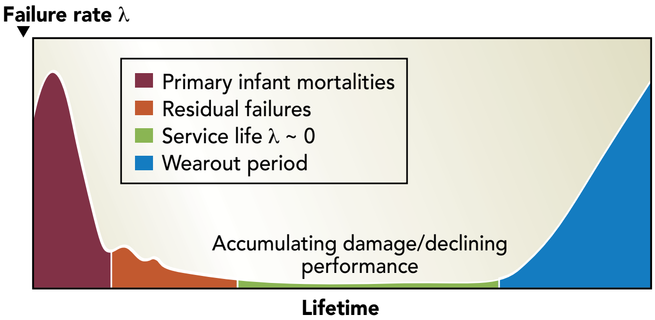


Figure 1. Failure rate vs. lifetime.

- Ultraviolet exposure [3]."

Reliability concerns associated with PV technologies

Quoting directly from a monograph [4] by Dr. Sarah Kurtz of NREL:

"General reliability issues across all PV technologies are:

1. Corrosion leading to a loss of grounding
2. Quick connector reliability
3. Improper insulation leading to loss of grounding
4. Delamination
5. Glass fracture
6. Bypass diode failure
7. Inverter reliability
8. Moisture ingress

Continuing, Dr. Kurtz said: "In addition, there are issues specific to the individual technologies, to name a few:

i. Wafer silicon: Light-induced cell degradation, front surface soiling, effect of glass on encapsulation performance, reduced adhesion leading to corrosion and/or delamination, busbar adhesion degradation, junction box failure;
ii. Thin film silicon: electrochemical corrosion of SnO_2, initial light degradation;

iii. CdTe: interlayer adhesion and delamination, electrochemical corrosion of SnO_2:F, shunt hot spots at scribe lines before and after stress;
iv. CIS: interlayer adhesion, busbar mechanical adhesion and electrical, notable sensitivity of TCO to moisture, moisture ingress failure of package; and
v. OPV: photolytic instability, moisture induced degradation, moisture ingress failure of package."

We often hear that people interpret passing the IEC 61215 or 61646 qualification tests is proof that a product has been tested and shown to be durable and reliable. This is simply not true; like many ALT tests, the IEC environmental stress test protocols are designed primarily to test the infant mortality period of the above-referenced bathtub curve (**Fig. 1,** pg. 11), and do not adequately or realistically stress a module in the way that nature does.

During life, a product loses performance attributes according to the accumulated damage model. Continued damage (thermal, photolytic, mechanical, hydrolytic, etc.) inflicted over a long time—and influenced by the daily and seasonal diurnal cycles—takes a toll.

According to Wohlgemuth, "While qualification tests are important, they have limitations because the stress levels are, by design, limited... so, passing the qualification test means that the product has met a specific set of requirements, but doesn't say anything about which product is better for long-term performance, nor does it provide a prediction of product lifetime [3]."

Reliability vs. durability

Classic reliability testing is primarily concerned with measuring outright failure, such as time to failure, mean time between failures, number of failures per "n" units or operations, etc. A variety of accelerated life test methodologies (ALT, highly accelerated life testing [HALT], highly accelerated stress screening [HASS], etc.) are used in this pursuit.

The general methodology is to apply higher (sometimes considerably so) levels of stress than actual use conditions—but over a shorter period of time—to try to

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predict longer term performance. This methodology carries the caveat that it may induce failures that would not naturally occur, but can be very useful for studying failure modes and product robustness.

Another ALT approach is to use near-normal stresses but applied over a much shorter time period (such as cycling of a door hinge). The IEC tests predominantly use the first approach; for example, the 85°C/85%RH damp heat test condition is not very realistic in terms of actual service. These ALT approaches work best for mechanically-related single-stress failures, and response is often non-linear for chemically induced changes or where degradation is dependent on sequential or overlapping mechanisms.

Durability testing, however, is primarily concerned with realistically stressing products to predict long-term performance and is concerned with routes to failure (mechanisms), rates of performance, or property loss, etc. A loss of material or product durability may lead to catastrophic failure (i.e, loss of reliability). Another critical aspect of "durability to the environment" testing is that weather and climate have multiple inter-related stressors varying continuously in both short- and long-term patterns—something extremely difficult to reproduce in basic test equipment.

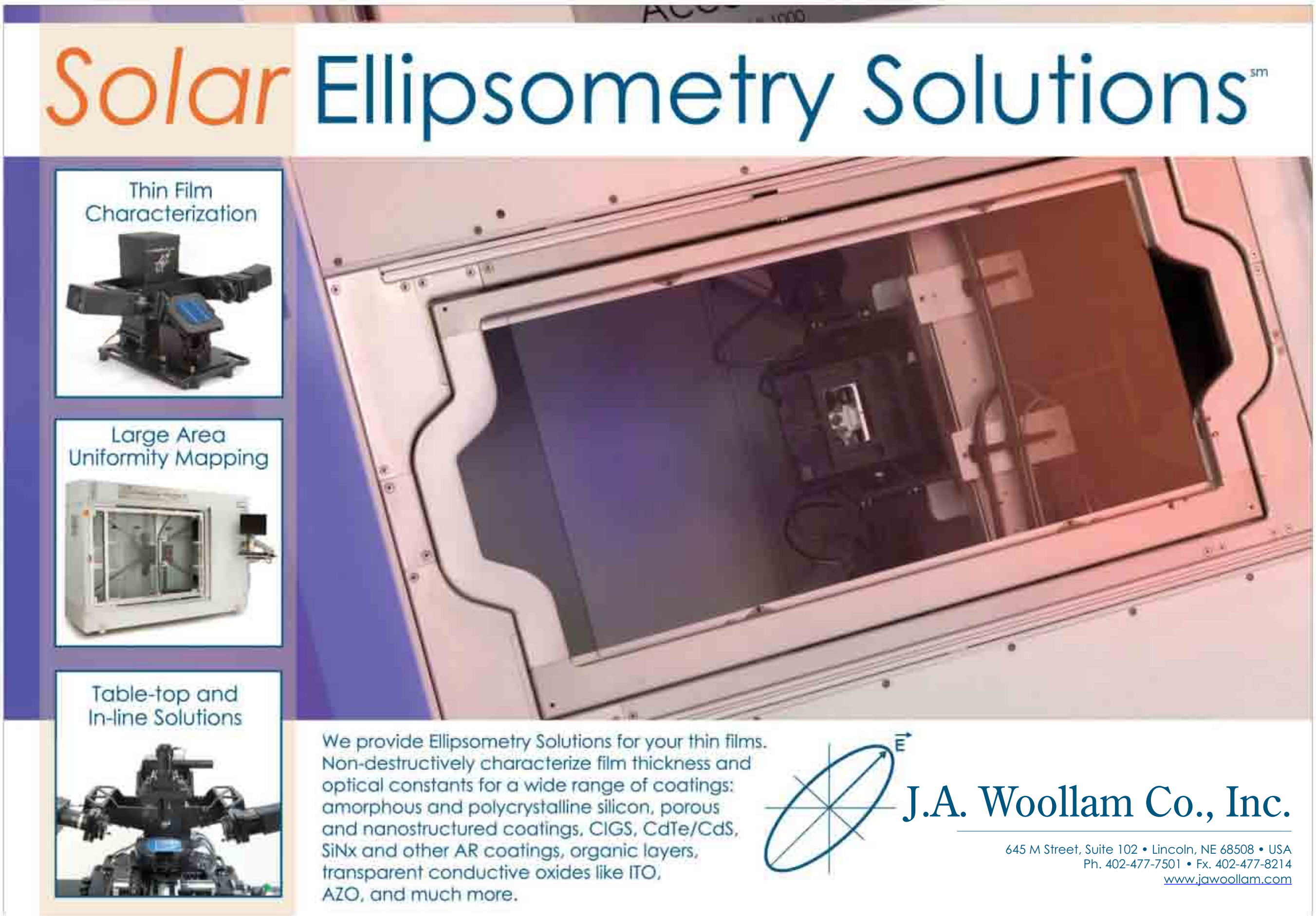
What is usually referred to in photovoltaics as "reliability," such as no more than 1% power loss per year to a maximum of 20%, is actually a durability issue.

A sequenced approach

Many other industries, such as automotive and building products, have long learned and developed a general testing approach to weather durability testing. While lifetime expectations or product complexity may be less than that for PV, the needs are the same.

The progession is:

- Material-level tests to select suitable products;
- Component-level tests to include processing variables and some material-material interactions; and
- Product-level tests to test final design and manufacturing, including transportation and installation.



To assess PV module durability, we usually start with the design failure modes and effects analysis (FMEA; or FMECA—failure modes, effects, and criticality analysis), and add a materials-level analysis. This helps to understand unique potential failure modes as well as potential test bias, both for optimizing the test methodology and for interpreting test results.

Next, materials-level tests are undertaken, especially for any polymeric materials (such as connectors, encapsulants, or topsheets) to determine their durabilities. We progress to component-level or pre-production unit testing, if warranted. Such testing can be helpful in determining processing variables, such as laminating conditions, or detecting basic problems, such as edge sealing or adhesion issues. The next step is full-module (or product, such as BIPV) testing.

An improved testing regimen

The primary module durability testing to date has simply relied on extending the existing IEC qualification tests to longer duration (e.g., more hours or more cycles). From our perspective, involving extensive work with PV materials and module manufacturers (as well as other industries) over the past years, and with millions of various products and materials on exposure in labs and test sites around the world, this approach has several flaws.

Although to study or force failure modes can have value for ALT testing, it isn't a realistic approach for estimating long-term weather durability. It limits the number of simultaneous stresses (such as temperature cycling without humidity or solar radiation), uses stress levels not representative of specific end-use climates, and fails to deliver the stresses in the complex short- and long-term cycles of the natural environment. In weathering testing, the rule is: do a different test (than nature), get a different result.

To improve weather test modules to predict the likelihood of 25+ years durability, Atlas has been developing an improved test methodology. The fundamental characteristics are:

- Parameters are selected based on three major PV use climatic zones: arid desert, tropical/subtropical, and northern/temperate, plus one additional global composite of all three sets of boundary conditions.
- Additional test modifiers of urban/industrial (e.g., hydrocarbons, soot); windblown dust/dirt; acid rain; mechanical loading; and coastal/marine.
- Combining multiple stresses into single test cycle modules, such as combined temperature and humidity cycling and humidity freeze with solar radiation to better simulate the natural environment.
- A series of test sequences, combining corrosion, condensing humidity, thermal/humidity/freeze/solar, outdoor solar tracking, UV preconditioning, etc.—all performed on the same module.
- Periodic visual inspections, I-V curve measurements, and thermal imaging.

Utilizing a variety of accelerated environmental testing (AET) devices and techniques, at realistic climate-specific stress levels and delivered in cycles that mimic the natural environment, this methodology can be run prior to, concurrent with, or following the IEC qualification tests, and is available now.

Conclusion

Service life prediction of complex products is an evolving discipline that often requires data and techniques that are not available. But while this methodology does not purport to address true SLP, it does have a 95-year foundation in empiricism shown to provide practical results. While no test program can predict with 100% certainty that a module will properly perform in an environment for 25+ years (except for real-time 25 year testing, of course), an improved methodology that more closely simulates the real environment while still maintaining reasonable acceleration can certainly be a valuable tool to answer the question, "Will my module last 25+ years?"

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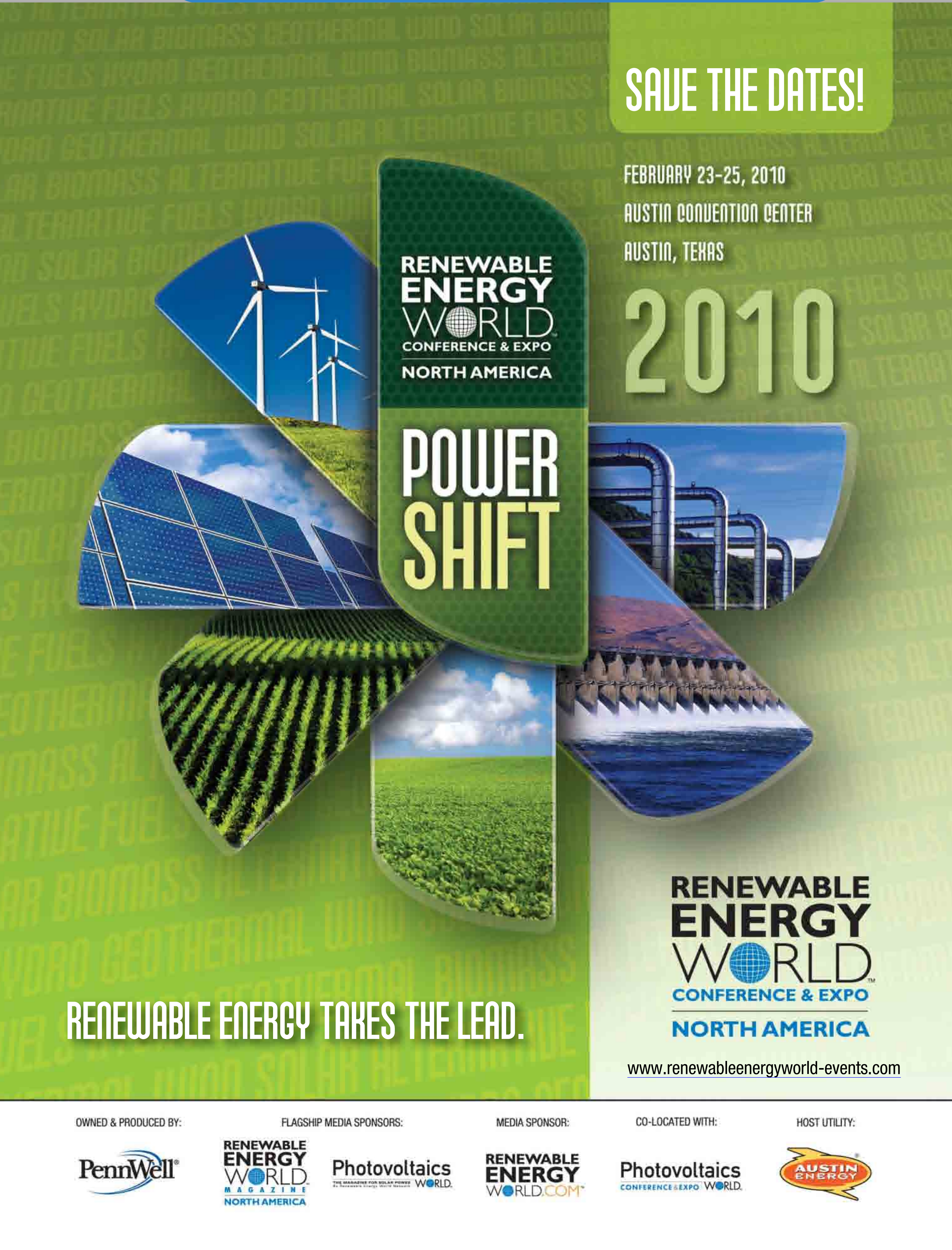
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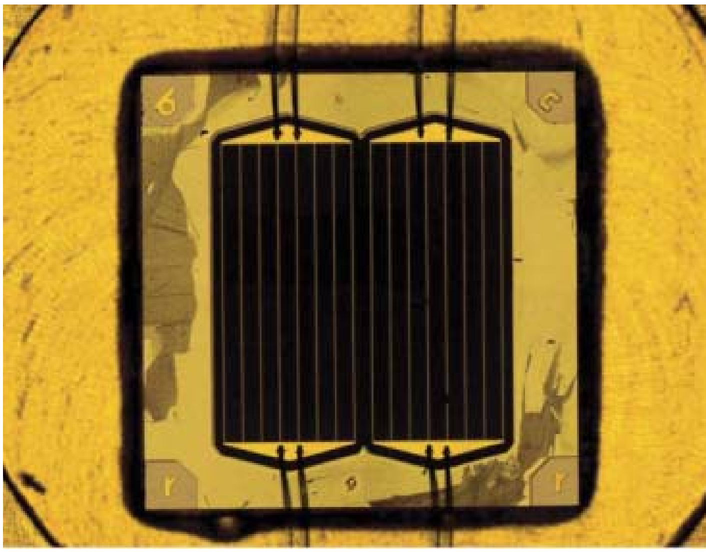
III-V thin films for PV applications

SIMON RUSHWORTH, SAFC Hitech, Bromborough, Wirral, UK

The rise in global interest in alternative and renewable energy sources over the past couple of years has seen the PV market expand rapidly, with bulk silicon solar cells dominating. But emerging technologies based on thin film devices are also making rapid progress, to the extent that this sector is now one of the largest growth areas being developed to help meet anticipated future PV needs. It is expected that by 2012, the rising production capacity of thin film technologies will account for more than 30% of total installed PV manufacturing (**Fig. 1**, pg.17).

The ability of the III-V materials system to maintain high efficiencies at high concentration levels using very thin films is particularly attractive in relation to reducing the volumes needed for the conversion process.



Techniques such as chemical bath deposition and closed space sublimation are leading the way in the fabrication of thin film solar cells. But there is also significant interest from the market in CVD (chemical vapor deposition) as a large area process on glass and other substrates. Competing material systems for the active thin films in PV manufacturing are cadmium telluride (CdTe) based, copper indium gallium (di)selenide (CIGS) based, and III-V materials--along with, of course, silicon.

III-V production considerations

For all solar cells, the efficiency of the active region at absorbing sunlight varies. In the III-V area, the conversion of light to electricity is most efficient at very high illumination levels; therefore, concentrator technologies are needed to generate around 500 suns, which is focused on the active area to achieve the best results. Under the highly demanding conditions applied to the active components, the structure of the complete cell must be perfect, and of very high purity with respect to a number of key contaminants to avoid internal losses due to non-radiative centers and the generation of excessive heat.

Significant experience in the area of III-V semiconductor deposition can be accessed via high brightness LED production technologies, since similar requirements for purity and control are needed to obtain the highest device performance. These approaches have led to the Fraunhofer Institute for Solar Energy recently achieving record efficiency levels using arsenide and phosphide materials. In particular, it has been observed that oxygen (O) is an unwanted non-radiative center that detracts from cell operating efficiencies and lifetimes. To minimize oxygen levels in the deposited films, the precursors used must be of the highest quality and, in particular, the organoaluminum source must have contaminant levels less than 1ppm.

In general, strict quality control of proprietary production and purification methodologies must be applied to ensure that the lowest contamination levels are available for PV applications, allowing generation of reliable, high-performance devices.

To achieve the targeted specifications, state of the art analytical capabilities must be employed to characterize the starting chemicals. For accurate oxygen contamination determination, significant problems exist due to the pyrophoric nature of many of the precursors used to deposit the optimum layers. In particular, group III metal alkyls, such as trimethylaluminum (TMA) and trimethylindium (TMI), require careful handling to avoid atmosphere contact due to high reactivity.

For example, any metal pipework or vessels contacted by the liquid or solid product must be totally O_2/H_2O-free. Typically, vacuum heat treatment for extended periods is necessary to desorb these species from surfaces and eliminate potential contamination. **Figure 2** (pg. 18) shows the impact on removal efficiency of residual gases with extended treatment protocols and the significant

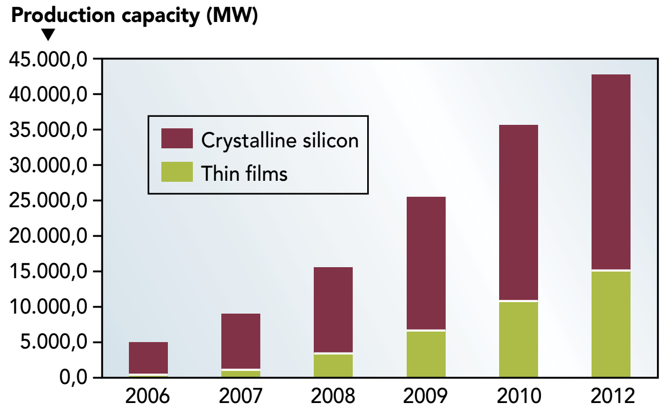


Figure 1. Forecasted PV manufacturing capacity for crystalline silicon vs. thin film technologies. (Source: Joint Research Centre Renewable Energy Unit–PV Status Report 2008; www.jrc.ec.europa.eu)

reduction of impurities observed. As shown in **Fig. 3**, 48 hour versus 24-hour vessel processing prior to product fill has been demonstrated to give improved performance in the most critical structures.

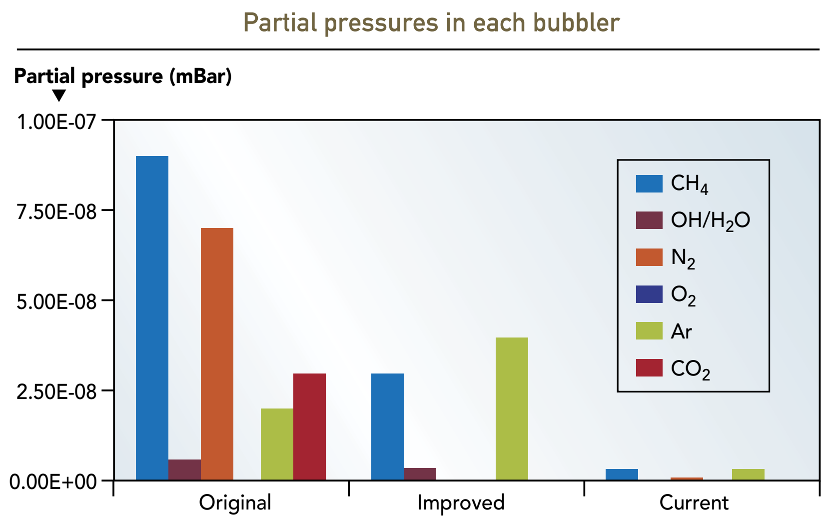


Figure 2. Residual gas analysis of vessels treated using different process parameters. (Source: Qinetiq–contracted trial with T. Martin group at Malvern, UK [not published])

Assessing the quality of the precursors themselves without actual growth testing requires careful correlation of physical impurity levels against reference values. For oxygen species, it has been found that the alkoxide peak present in the product proton nuclear magnetic resonance (NMR) can be directly used to indicate performance in growth. **Figure 4** (pg. 19) shows the detected O species levels in a series of trimethylaluminium (Me_3Al) samples, and **Table 1** highlights the properties of aluminum gallium arsenide (AlGaAs) deposited using these samples. A direct correlation between the two sets of data is clearly seen, with contamination levels of less than 1ppm in the source demonstrated as key to achieving the highest final film quality.

Delivery system developments

The requirement for larger volumes of precursor to allow large area deposition at high throughput and low cost has led to a number of innovative equipment developments targeting bulk delivery of chemicals to the growth tools. Safer handling of increased lot sizes helps to reduce the overall cost of ownership for the deposition processes by minimizing tool downtime and qualification run requirements. The use of larger batches and the above economies of scale without compromising quality are key elements in enabling customers to achieve economically viable processes and meet increasing consumer demands in a robust and sustainable manner.

For liquid precursors, the preferred method of bulk delivery involves pumping product to the tool for vaporization, as is normally employed for smaller batch sizes. The advantage of this approach is that it offers easy retrofitting to existing equipment without the need to change process parameters. In addition, the benefits in cost of ownership are significant for production tools running the same process continuously.

To optimize output, the loading on all deposition tools should be as close to 100% as possible, since downtime replacing or changing out bubblers when a precursor lot has been depleted and requires refilling can be detrimental to the economics of the process. By adding the ability to refill the tool container and immediately resume production on the fly at the touch of a button, time and money can be saved. Obviously, the safe movement of highly hazardous

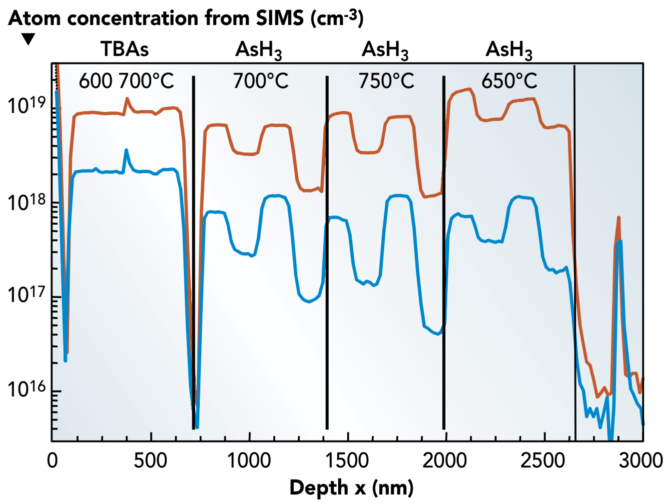


Figure 3. Oxygen level in AlGaAs-based structures grown under a variety of conditions, with Me_3Al filled into containers treated for 24 hours (orange trace) and 48 hours (blue trace). The lower the O level, the better; hence, 48 hours is better than 24-hour treatment of the bubbler. (Source: Fraunhofer Institute for Solar Energie–contracted trial with F. Dimroth group at Freiburg, Germany [not published])

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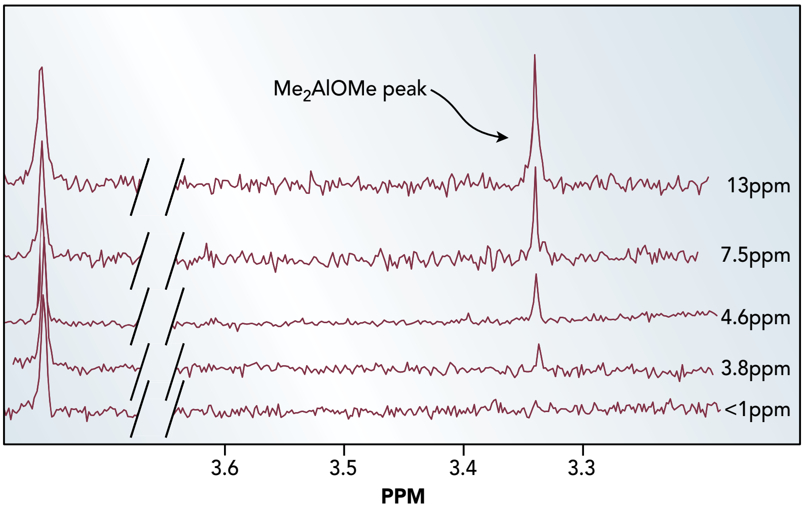

Figure 4. Alkoxide contamination quantification in Me_3Al samples using proton NMR. (Source: SAFC Hitech in-house analysis)

chemicals between two points requires specifically engineered equipment, and precursor suppliers have applied their expertise to the design of such systems as SAFC Hitech's EpiFill.

An alternative approach for solid precursor delivery, or where simplified deposition tools are to be installed, is a bulk vaporization unit; it can supply precursor vapors directly to the deposition chamber via a mixing manifold only, thus removing the necessity for multiple, individually-controlled temperature environments on each system. As for the liquid case, the cost advantages of reduced downtime are attractive and, by moving the evaporation stage away from the growth kit, the control of gases entering the deposition chamber can be addressed without resorting to complex systems, making process control more reliable. Again, chemical suppliers have employed their expertise to develop robust equipment to deliver the desired volumes of precursor vapors in a safe, reliable fashion.

New levels of solar cell efficiency

The impact of controlled precursor provision as an

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TMA sample number	O level in TMA using new NMR technique (ppm)	[O] in $Al_xGa_{1-x}As$ by SIMS (cm^{-3})		Composition
		p type (C) 3-5E18cm^{-3}	n type (Si) 1-3E18cm^{-3}	
1	>30	$1x10^{19}$	$8x10^{18}$	X=0.9
2	13	$1x10^{19}$	$2x10^{18}$	X=0.9
3	7.5	$1.5x10^{18}$	$6x10^{17}$	X=0.9
4	6.0	$6x10^{17}$	$1.5x10^{17}$	X=0.9
5	4.6	$1x10^{17}$	$1x10^{17}$	X=0.9
6	3.8	$2x10^{17}$	$4x10^{16}$	X=0.9
EpiPure TMA	<1ppm (ND)	$<3x10^{16}$ (ND)	$<3x10^{16}$ (ND)	X=1

Table 1. Correlation of O levels in Me_3Al precursor and AlGaAs films. (Source: Fraunhofer Institute for Solar Energie, contracted trial with F. Dimroth group at Freiburg, Germany [1])

enabling technology is illustrated by the advances made in the field of III-V thin film solar cells where, as noted earlier, record efficiencies are being achieved using high purity products. The reliable supply of such chemicals has enabled process and device optimization to be performed with the confidence that the composition of thin film structures can be controlled precisely and reproducibly across the range of test parameters employed to identify device improvements.

Monolithic multi-junction solar cells based on epitaxial III-V semiconductors have evolved over many years to the point at which purity and crystallinity levels are now extremely high. This is reflected in the rise in efficiencies over this period for the most successful designs. The latest three PN-junction combinations with gallium indium phosphide ($Ga_{0.35}In_{0.65}P$), gallium indium arsenic ($Ga_{0.83}In_{0.17}As$) and germanium (Ge) absorb sunlight across the ranges 300-780nm, up to 1020nm, and up to 1880nm, respectively, which has been predicted as particularly advantageous for the terrestrial solar spectrum conversion to electricity.

A new record-breaking solar cell from the Fraunhofer ISE has a cell area of 5.09mm^2 and an overall efficiency when operated at 454 suns of 41.1%. The ability to operate at even higher concentrations while keeping high efficiency (37.6% @ 1700 suns) is a key advantage of this cell design, but this function is highly dependent on perfect construction of all the individual layers and interfaces to avoid charge trapping and more problematic defect propagation. The degradation of quality by such methods leads to reduced lifetimes, which are not acceptable in a commercial device; hence, the focus on deposition technologies to achieve high-quality epitaxy throughout the multilayer structure.

Conclusion

To achieve record-breaking values for solar cell efficiencies and to continue to improve cell performance in the future, a complex structure with up to 40 individual layers must be prepared perfectly. Therefore, robust growth processes and precursor delivery capabilities that maintain high purity and offer high controllability at high volumes are of critical importance.

Performance maintenance through the scale-up of these processes will lead to production cost reductions. Furthermore, the ability of the III-V materials system to maintain high efficiencies at high concentration levels using very thin films is particularly attractive in relation to reducing the volumes needed for the conversion process. This, in turn, will further reduce electricity generation costs in the future, helping to drive this technology to the forefront of PV solutions for alternative energy supplies on a global scale.

Acknowledgment

EpiFill and EpiPure are trademarks of SAFC Hitech.

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Lock-in thermography enables solar cell development

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Currently, PV cells suffer from various manufacturing problems that limit their conversion efficiency. Additionally, conversion efficiency varies according to the technology employed, with silicon PV cells achieving conversion efficiencies between 15% and 25%, while typical metallic thin film cells have efficiencies in the 5% to 20% range (depending on materials used).

Lock-in techniques greatly increase the sensitivity and image resolution of thermography used in PV cell defect detection.

Much of the industry's R&D efforts are aimed at reducing production defects. Too many defects in the semiconducting material structure go undetected before PV cells are put into solar panel assemblies. Identifying these defects requires efficient, cost-effective test and measurement methods for characterizing a cell's performance and its electronic structure.

Sources of defects

A PV cell is typically modeled as an ideal diode in parallel with a photocurrent source, plus parasitic resistances, such as shunt resistance (R_{SH}) and series resistance (R_S) (**Fig. 1**).

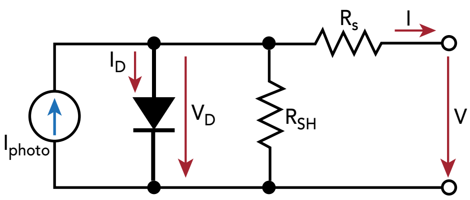
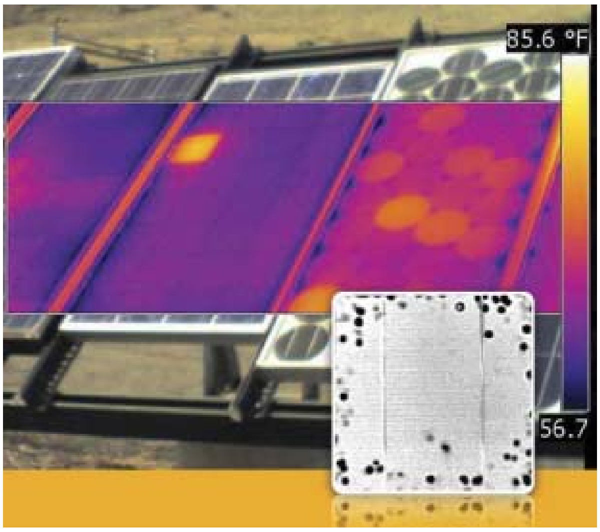


Figure 1. Circuitmodel of a PV cell.



The conversion efficiency of silicon PV cells is limited by free carrier recombination, due to bulk material defects. This is especially true in multicrystalline silicon (mc-Si) wafers, which have significant concentrations of crystallographic non-uniformities, such as dislocations, grain boundaries, and impurities.

In thin metallic film PV development, lateral non-uniformities in current flow across a cell are troublesome [1]. Since larger solar panels are constructed by connecting individual PV cells, a few bad cells can affect the performance of the entire assembly. Often, a high R_{SH} results from:

- Improper handling during processing;
- Diamond saw scribing at cell boundaries;
- Over-firing during cell metallization;
- Poor edge isolation processes [2,3];
- Random shunts inherent in most production processes.

The dominant sources of R_S are contact resistance, bus bar resistance, screen-printed "fingers," and lateral conductions in the emitter. The relative importance of each source depends on bias level and current flow.

To determine the sources and magnitudes of defects, the parameters most commonly measured include resistivity (to screen wafer material) and characteristics of production cells, such as I-V and C-V curves, charge carrier characteristics/current density, free charge recombination lifetime, bulk material lifetime, and effective lifetime.

Test techniques vary greatly in terms of complexity, equipment cost, and the time required for a typical set of measurements. The three broad areas of test technology are spectroscopy, electrical (contact) measurements, and infrared (IR) imaging. Frequently, multiple techniques are used [4].

Electrical C-V, I-V, and resistivity profiling in early production stages require wafer probing and thickness measurements. The latter require additional optical or capacitive gauging techniques. Some of these may also require time-consuming sample preparation.

Conventional IR imaging methods

Testing via infrared imaging has been used for more than a decade, and is growing in importance because it is relatively fast and with moderate equipment cost. The IR cameras are basically video devices, but each video frame is accessible as a still thermographic image, whose digital content is also available—including actual temperature data. Standard thermographic imaging of a PV cell quickly reveals major shunt defects during the application of reverse bias (**Fig. 2**), or by just observing the temperature of the cell under typical operation.

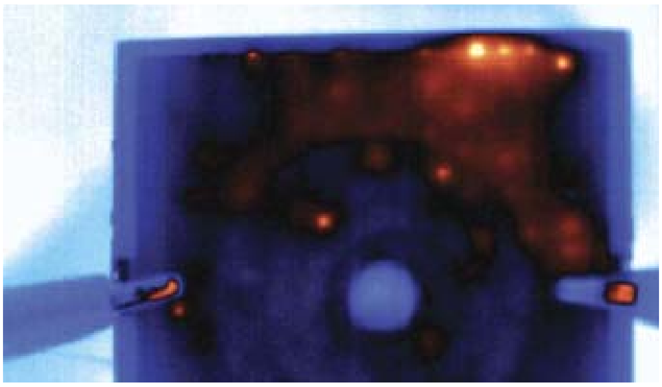


Figure 2. IR image of 60x60mm silicon solar cell showing shunt defects (orange areas) under steady state reverse bias conditions. (Triangular shapes on the left and right are alligator clips that apply bias voltage; the circular blue area is a reflection of the IR camera lens.)

The sensitivity and thermal resolution of standard thermography, however, is limited by an IR camera's inherent detector sensitivity or noise equivalent temperature difference (NETD). The NETD for cameras with cooled indium antimonide (InSb) detectors is ~20mK; it's ~80mK for an uncooled microbolometer detector. Only severely shunted areas are visible. The darker orange regions in **Fig. 2** result from weaker shunt defects. Locating the origins of weaker shunts is extremely difficult, if not impossible, due to the thermal diffusion (spreading of thermal energy over time), as well as the weak thermal radiation of the defect itself.

Visible light cameras are largely ineffective at revealing even major defects, but provide useful reference points alongside an IR image. Today, IR cameras are available that combine both thermographic and visible light imaging, making fast steady-state testing of solar cells very convenient.

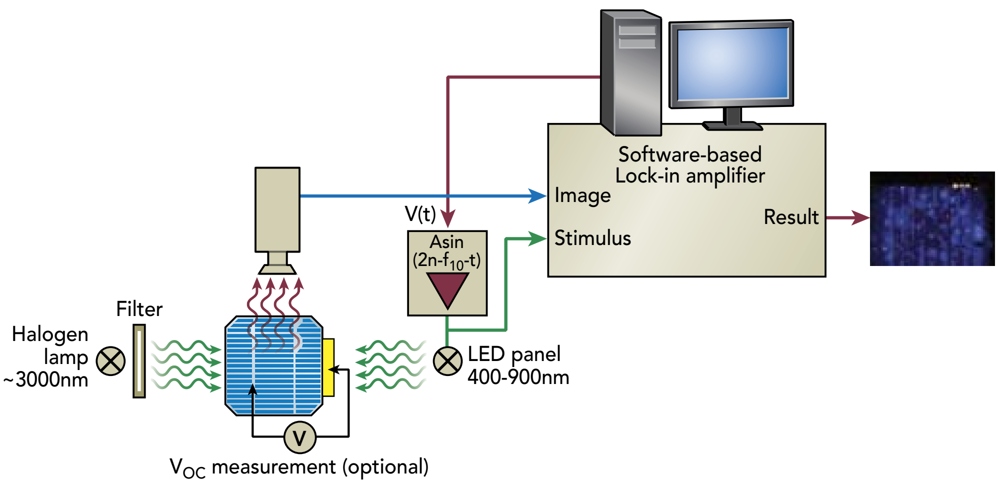


Figure 3. Non-contact LIT test system (SolarCheck by MoviTHERM, uses modulated light as the PV cell stimulus. (Optional V_{OC} measurements do require electrical probing of the cell). The system uses a FLIR IR camera with an uncooled microbolometer detector.

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A variation in conventional IR imaging of defects is to move a heat lamp and camera attached to a fixture across the surface of a PV cell or a solar panel. This methodology can improve the crack detection rate and reduce inspection time. The drawback of using a "slow" heat or excitation source is that the resulting thermal diffusivity will be significant, negatively affecting the spatial resolution and definition of the crack.

Refinements to conventional IR imaging

To minimize the thermal diffusion that occurs with slow stimuli, pulsed or sinusoidal stimulation can be used. This can take the form of applied electrical signals or light.

Electroluminescence (EL) and photoluminescence (PL) techniques. EL and PL are techniques used to generate spatially resolved images of solar cells that reveal localized shunts, series resistance, and areas of charge carrier recombination [2,5]. EL applies a forward voltage and current to cause localized irradiance due to carrier recombination. PL uses light irradiation for the same purpose. In both cases, the stimulus can be applied as a pulse.

In EL testing, current flow causes the PV cell to emit light in the near infrared (NIR) range of the spectrum. The resulting thermographic image provides a visual representation of a PV cell's uniformity with respect to its ability to convert photons into electrons. Care must be exercised to avoid applying a destructive amount of current to the cell.

Since EL and PL techniques only work in the NIR region, both types require a camera with a cooled NIR detector. (Uncooled microbolometer detectors are longwave IR instruments and, therefore, not suitable.)

Lock-in thermography (LIT). Commercially available lock-in thermography systems are overcoming the limitations of conventional thermal imaging. Typically, they use a xenon or halogen flash lamp, or a modulated laser as the excitation source. In LIT measurements, the test system synchronizes the excitation source to the camera's data acquisition (**Fig. 3**), which collects a sequence of hundreds of images.

Advantages of LIT

By stimulating a PV cell with pulsed light, heat, or electrical signals, a lock-in amplifier tuned to the stimulus' excitation frequency allows the system to detect subtle thermal responses beyond the noise floor limitations of an IR camera. The increased sensitivity brings the system's detection threshold down below the noise floor by a factor of 100 to 1,000. In addition, this type of system has the distinct advantage of eliminating problems due to reflections from other heat sources, such as human body radiation, overhead lights, etc.

Figure 4 is an image of the same PV cell used for **Fig. 2**, but collected with the LIT system shown in **Fig. 3**. Note that the image resolution in **Fig. 4** is much better (i.e., not diffused and blurry), with localized shunt defects more sharply defined by the orange areas. The sharper image provides other information, such as non-uniform heating of the cell, as revealed by lighter and darker blue areas. In addition, the reflection of the camera lens and outlines of the alligator clips no longer obscure large portions of the image, as they do in **Fig. 2**.

This LIT technique allows mapping of forward current density distribution, and can also reveal series resistance and sites where there is heightened carrier recombination [6-8]. It requires significantly less energy input to a solar cell compared to conventional thermography.

LIT test variables

In using LIT for shunt detection, the stimulus' modulation frequency is important because it affects thermal diffusion and image resolution. In conventional electrical measurements using lock-in amplifiers, the tendency is to lower the stimulus frequency to only a few Hz to get below the frequency of most noise sources. This has to be modified somewhat in LIT. Typically, the order of magnitude for a stimulation frequency is ~100Hz. If the stimulation frequency is an order of magnitude lower (~10Hz), thermal diffusion becomes so great that defects tend to disappear from the LIT image.

With proper selection of the stimulation frequency, thermal image resolution is limited primarily by the pixel resolution of the camera's focal plane array detector and its optics. For the camera used in **Fig. 3**, the detector pixel size is 25μm. Microscope optics are available that are capable of 6μm/pixel spatial resolution.

Images and cell parameters are calculated by the system software running on a PC. With appropriate software, the processed signal from the IR camera's detector can be used to make quantitative measurements of I-V characteristics associated with a localized shunt, calculate the reduction in cell efficiency due to shunts, and map saturation current density and ideality factor over the entire cell.

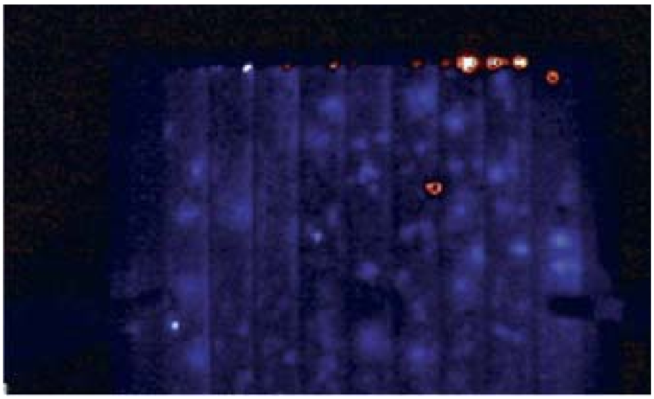

Figure 4. Image of the same solar cell in Figure 2, now showing shunt defects more clearly (orange areas) when mapped with an LIT technique. (Image from a SolarCheck system.)

Quantifying charge carrier behavior

With LIT systems and software, charge carrier behavior in PV wafers and cells can be characterized. Charge density imaging (CDI) is particularly advantageous as it can rapidly map saturation current density and other parameters over an entire PV cell [9,10].

Flash CDI is based on free-carrier absorption of photo-generated excess carriers, and thus allows the imaging of charge carrier lifetime properties. Carrier generation is controlled by adjusting the laser intensity to approximately a 1-sun level. With lock-in processing of the signal, much shorter lifetimes can be measured. Test time can be on the order of seconds, and an entire CDI wafer map can be created in a minute or so. (Actual CDI test times depend on the length of the effective lifetimes being measured.) Image resolution is better than that obtained with many other techniques, some of which are an order of magnitude slower.

Typical PV cell parameters of interest include short circuit current (I_{SC}), open circuit voltage (V_{OC}), fill factor (FF), ideality factor (η), series resistance (R_S) at V_{OC}, shunt resistance (R_{SH}) at 0V, and reverse voltage breakdown. FF and η are usually derived from I-V measurements.

To a great extent, cell efficiency is largely a function of I_{SC}, V_{OC}, and FF. V_{OC} and FF can be characterized by the shape of the forward biased dark I-V curve. Frequently, distribution of forward current density over the entire cell is inhomogeneous. If current density through a given region is higher than the cell average, this is indicative of a shunt. Therefore, characterizing shunts under forward-bias conditions is important in the efforts to increase efficiency.

Parasitic RS is important as it contributes to FF losses and ideality factor (η). R_S is typically determined from a set of illuminated and dark I-V measurements. While these are straightforward, collecting a complete set of I-V measurements can be time consuming.

Parameter extraction is done by assuming carrier lifetime is homogeneous over a particular sample width, and applying a sinusoidal correlation procedure. The intensity of each pixel, I_A, can be determined by:

$$I_A = k \, \Delta m \, W,$$

where k is the sinusoidal correlation factor, m=excess minority carrier concentration, and W is the sample width.

Basing the camera's frame rate on the lock-in frequency allows for carrier density measurements to be taken under a steady-state condition during each half period of the stimulus signal. The steady-state measurement of Δm values can be used to calculate effective carrier lifetime according to:

$$\tau_{eff} = \Delta m W / G = I_A / -kG,$$

where G is the local generation rate for the sample area.

Because a PV cell can be modeled as an ideal diode in parallel with a photocurrent source, LIT can be used to thermally measure local I-V characteristics that reveal non-ideal behavior (i.e., parasitic series and shunt resistance).

Non-ideal diode properties of the PV cell are also expressed in the ideality factor,

$$\eta = \delta V / \delta \ln(I).$$

By accounting for R_S and R_{SH}, the relationship between η and PV cell voltage can be established, which leads to a better understanding of charge carrier transport mechanisms.

LIT can be combined with illuminated and dark I-V measurements to derive other PV cell parameters. For example, FF is lower than ideal due to R_S and R_{SH}, and can be expressed as:

$$FF = I_{mpp} V_{mpp} / I_{SC} V_{OC}$$

where mpp is the maximum power point.

Conclusion

A major advantage of LIT compared to many other test methods is the short time required to complete a set of measurements without elaborate sample preparation. Once an LIT system is configured, significant amounts of data can be acquired in seconds, compared to minutes or hours with other methodologies. This makes LIT a good candidate for process-related testing, as well as for use in the R&D lab to detect cracks, shunts, parasitic series resistance, and localized charge carrier characteristics.

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Off-line APCVD offers paradigm shift for TCO glass end users

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The introduction of off-line systems will revolutionize the way that transparent conductive oxide (TCO) glass end-users can run their business. Presently, commercially available systems for deposition of TCO thin film coatings come in two forms:

- *Physical vapor deposition (PVD) systems,* specifically, sputtering systems, where an Ar-ion cloud bombards a target to strip material from the target, and allows it to deposit on the substrate;

The benefits of atmospheric pressure chemical vapor deposition (APCVD) for TCO-coated glass have been clearly demonstrated, and the opportunity to apply this technique to TCO thin film depositions has helped to improve cost and availability of glass products.

- *On-line (integrated with float glass lines) APCVD systems,* which utilize heat to convert liquid or precursors into durable solid thin films. This technique is presently limited to deployment by glass manufacturers.

Offering lower cost operation, significantly lower power consumption, and superior film properties, APCVD is a compelling option for the glass industry. Any business is cost-sensitive, but consumers of TCO-coated glass are in the business of sustainability and alternative energy, meaning that in addition to cost savings, lower power consumption has a special incentive. Currently,

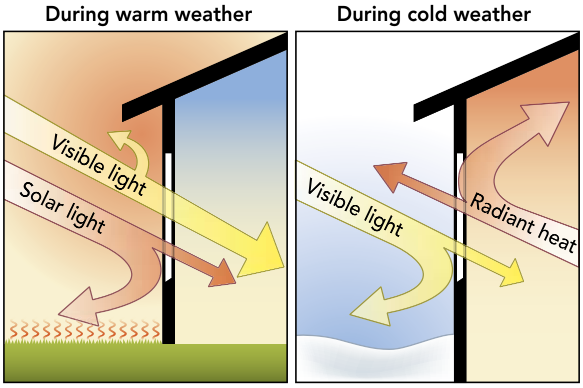

Figure 1. Function of a Low-e window.

there is no commercially available APCVD coating equipment that would allow the lower cost and off-line functionality necessary for a realistic effort on the part of TCO glass end-users to embark on a path of independence.

TCO-coated glass has found many applications in the last decade and has created a multibillion dollar market. The main applications are energy saving, low scattering (Low-e) coatings for architectural windows (**Fig. 1**), and high scattering TCO coating on glass for a wide variety of photovoltaic (PV) thin film modules and TCO-coated glass for display applications. The worldwide expected demand for TCO glass by 2012 is greater than 500 million m^2 per year, which represents a market opportunity for TCO-coated glass well above $10B per year.

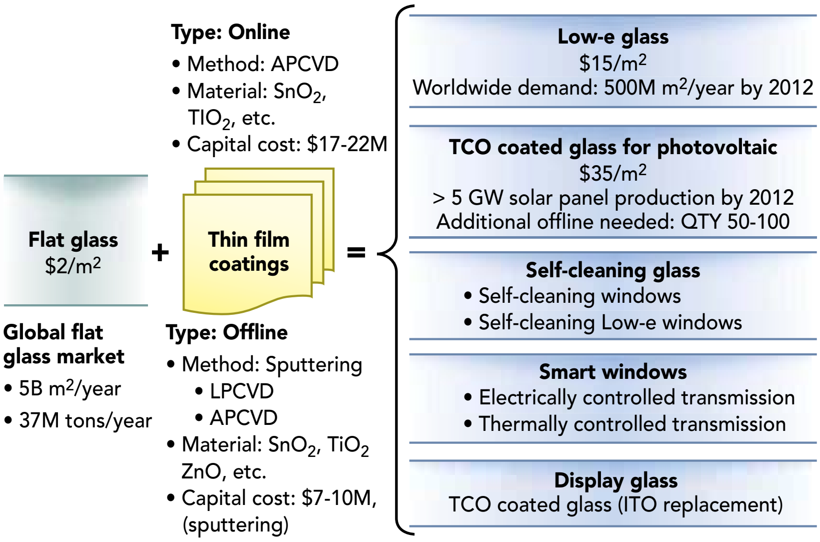

Figure 2. Cost for processed glass.

APCVD advantages

The two primary TCO coating technologies used to coat glass on a large volume scale are APCVD and PVD. In general, APCVD manufactures much more durable TCO coatings than PVD, consumes between 10-50% of the energy, and produces coatings at less than half the cost (**Fig. 2**). Traditionally, the two compelling reasons for PVD have been availability of commercial systems and easier process changeover. Moreover, the complexities of the APCVD systems meant they were out of the technical reach of TCO glass end-users. But a commercially available off-line APCVD system, from a company with decades of experience in a myriad of CVD applications, overcomes both challenges to adoption, and lets end-users enjoy all the benefits of the APCVD method.

There are several benefits from using APCVD:

- *No vacuum.* APCVD does not require a vacuum (low pressure) atmosphere as does PVD; thus, a lower capital cost.
- *Lower operating cost.* APCVD uses gas, liquid chemical sources and heat to produce a thin film, compared to expensive sputtering targets, plasma, and vacuum used by PVD, resulting in up to 50% lower operating costs.
- *Film quality.* APCVD-deposited TCO films have better hardness/adhesion.

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Operational constraints

TCO films deposited using PVD (AZO) are highly susceptible to physical damage and moisture due to their relatively low chemical stability against weak acids. For this reason, these TCO coatings force certain operational constraints upon end-users, including:

1. **Need for hermetic sealing.** PVD sputtered coatings must be hermetically sealed within a mechanical structure. A sputtered TCO film cannot be on the outside face of the final glass product. Moreover, it must be contained within the interior of the final assembly within three weeks of manufacture, or degradation of the TCO film will occur and its beneficial properties severely reduced or negated. In the case of thin film solar module applications, degradation translates directly to reduced lifetime. In both Low-e windows and solar modules, relatively common seal failures have a direct impact on energy performance because these films are not resistant to common atmospheric conditions.

   TCO films made by APCVD are much harder with much better adhesion, allowing the final window, display, or solar panel to be assembled in whatever manner is technically or operationally superior—on the inside or outside of the assembly. There are no shelf life considerations before assembly, and the panels will continue to deliver energy performance even in the event of a seal failure.
2. **Higher stability.** APCVD TCO glass can be ordered well in advance due to its much higher stability. When ordering glass material, which is already coated, the end users of TCO glass (i.e., manufacturers of windows, displays, or thin film solar modules) can order larger volumes without the concern of a three-week shelf life, as with PVD sputtered TCO glass.
3. **Less sensitivity.** Less sensitivity to moisture and physical handling means that APCVD-coated glass can be bought in any size and cut to order at the panel assembly company.

Many of the aforementioned benefits apply equally well to manufacturers and end-users of sheet glass. Moreover, the benefits of APCVD TCO coatings are compelling, whether deployed as an on-line or off-line system. Indeed, such systems have been commercially available for some time (in an on-line form factor only), and glass manufacturers and their customers have been well served by this availability.

Online benefits

It is also recognized that the *on-line* APCVD system offers certain compelling benefits, including:

1. **Pre-heated glass.** The glass is already heated to APCVD process temperatures from the float glass manufacturing process;
2. **Clean glass.** There is no pre-deposition cleaning step required since the glass arrives clean to the deposition area;
3. **Footprint.** There is no need of separate floor space;
4. **Recycling.** Defective glass can be recycled and reused as raw material for glass manufacturing since it is still at the manufacturing facility when coated.

Float glass line limitations

But the potential mismatch of the line speed of a float glass line and the process window of a chosen APCVD process mitigates these advantages. Generally, this limits the APCVD film deposition choices for a given on-line APCVD system. With precursor selections for APCVD improving all the time in response to evolving market demand, the narrow line speed window of a given float glass line severely limits the ability to adjust to market demands. In fact, with a constant pressure to make glass thinner for PV markets, float glass lines (which run at a constant line speed inversely proportional to the glass thickness) will be even more likely to be limited by the coating process going forward.

At present, APCVD TCO films with the highest performance specifications (8Ω/□) are only available from glass manufacturers deploying an off-line coating strategy that allows them the freedom to deposit a thicker film than is commercially practical for an on-line system. Ultimately, this on-line dynamic will logically force a compromise in the form of thinner film depositions and/or lower performance parameters.

CVD is a process that operates under the combination of four physical attributes: temperature, pressure, deposition time and precursor flow rate. The first two variables are absolutely fixed for an APCVD on-line system; temperature depends on the location of the APCVD system on the float glass line (typically, 700-500°C), and pressure is atmospheric. The deposition time depends on the line speed, total deposition area, and the precursor flow rate(s). If an inappropriate parameter region is selected, the deposition modules must be moved off-line more often for cleaning/

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servicing, leading to a limited uptime. Moreover, changeover of precursors for various applications, and the need for multi-film layers for solar applications on a moving line is clearly challenging (**Fig. 3**).

Due to these considerations, it is clear that only an off-line APCVD system, which additionally allows tuning of the line speed to the optimum process window of a chosen APCVD precursor chemistry/system, has the power to change the way the market operates. Such equipment will be commercially available starting in 2010.

Historically, APCVD TCO glass has only been available by online APCVD deposition systems, which are mostly home-built by the major players in the glass manufacturing industry (although commercial systems are recently available). Indeed, the benefits of APCVD coating technology are available to those willing to build a new \$100-\$150M float glass line and to add an online APCVD system, either purchased or developed in-house. Therefore, end users have only had the choice of purchasing TCO-coated glass from a glass company with on-line APCVD coating technology, or to purchase an off-line sputtering TCO coating system and live with its limitations.

Because the supplier who has made the past investment is presently depositing TCO with a technology offering far superior quality and lower cost than anything available to the typical end-user, end users are left with little choice. The significant premium they pay for TCO-coated material—~\$15-\$35 /m^2—is the result of this predicament.

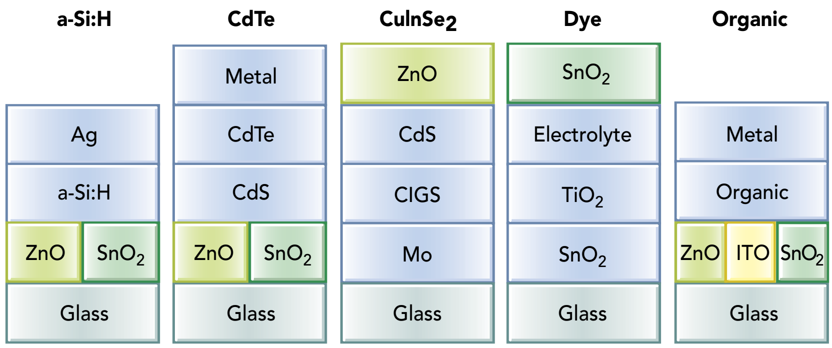

Figure 3. TCO use in solar cells.

Off-line turnkey solution

End users will soon have a new option—a commercially produced, off-line APCVD turnkey system, which clearly lays the groundwork for a paradigm shift in the business model for these end users. Depending on market conditions and business considerations, end users can buy their glass with TCO coating, or buy unprocessed glass and coat internally with their off-line systems. This approach is especially productive for smaller to mid-size volume users, allowing a glass end user to deposit custom-tuned TCO for Low-e architectural glass, or thin film PV modules as per their own specifications and customer demand.

Chemical vapor deposition (CVD) generally offers superior thin films compared to PVD. But bilding such a system is not trivial, and this complexity has been a significant impediment to the adoption of CVD for TCO applications, since only companies with very significant resources could successfully build, ramp, and integrate such a system.

The benefits of APCVD for TCO-coated glass have been clearly demonstrated for some time, and the opportunity to apply this technique to TCO thin film depositions has helped to improve cost and availability of glass products requiring these films. Allowing this technology to move downstream is taking it to the next level. It is only by providing a method for off-line APCVD to go downstream to the end user that we can really open up multiple opportunities in terms of operational flexibility.

Conclusion

Today, window and PV panel manufacturers have three choices: clear glass for ~\$2/m^2, Low-e glass for ~\$15/m^2, or PV TCO glass for ~\$35/m^2. Thanks to the availability of a professionally designed and built off-line APCVD system with a predictable process ramp and high tool availability, these end users—now vertically integrated—can sell their TCO-based products with a cost basis closer to one-third to one-half of the usual numbers.

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Karlheinz Strobl received his PhD through Max Planck Institute/U. of Innsbruck, and did post doctoral work at Los Alamos National Laboratory. He holds an MBA from Boston U., and is VP of business development at CVD Equipment Corp; 631-981-7081; kstrobl@cvdequipment.com

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PV metallization pastes

DuPont Microcircuit Materials' Solamet PV412 metallization paste, developed with Ascent Solar Technologies, is for devices built with transparent conductive oxides (TCO), including copper-indium-gallium-selenide (CIGS), amorphous silicon (a-Si) on flexible substrates, and heterojunction with intrinsic thin layers (HIT) PV cells. Key features include fine line printing down to 80μm resolution, low contact resistance, and high ITO adhesion.

Heraeus' SOL9235H front-side silver paste for mono- and multicrystalline silicon PV cells works with a wide range of sheet resistance emitters, according to the company. Customer tests reportedly increased cell absolute output efficiencies by 0.2%-0.4% in development and scale-up.

DuPont Microcircuit Materials, Research Triangle Park, NC; ph 919/248.5598, ellen.g.pressley@usa.dupont.com, www.dupont.com.

Heraeus PV Materials, West Conshohocken, PA; ph 610/825.6050, gail.strong@heraeus.com, www.pvsilverpaste.com.

Gel-based ARC

The SolarC is a gel-based antireflective coating for PV modules that improves light transmittance and damp heat resistance of module glass—more light reaching the cell means more electricity is generated. It requires no mixing of components, and works with all common types of PV modules and is compatible with spray, roller, curtain, slot-die, and spin-on coating processes. The company claims demonstration of a 4% increase in transmission at 550nm.

Honeywell Specialty Materials, Morris Township, NJ; ph 973/455.4908, Peter.Dalpe@honeywell.com, www51.honeywell.com/sm.

Wafering system with diamonds, no slurry

The HCT Diamond Squarer system uses diamond particles bonded to a metallic wire core to cut the silicon ingot at least twice as fast as conventional squaring systems using abrasive slurry, reducing the process cost by up to one-third and halving electricity consumption. Kerf loss is 0.30-0.35mm vs. 1.5-3.5mm for band/OD saws. Load capacity is one cast ingot or 16-25 mono ingots. Upgrade kits are available for currently installed HCT Squarer systems.

Applied Materials Switzerland SA (formerly HCT Shaping Systems), Cheseaux, Switzerland; ph 41/21.731.9100, www.appliedmaterials.com.

Modular thermal processing for CdTe

The Perseas modular platform is designed for processing cadmium telluride (CdTe) thin-film PV cells, with one module for the chlorine annealing process (300°C, ±5°C uniformity, 50-100 panels/hr) and another for contact formation (600°C, ±3°C uniformity, 50-150 panels/hr). An "active load monitoring" technology reduces likelihood of scrapped panels, increasing yields. The platform can handle glass substrates up to 1.3m wide, and also is compatible with web substrates.

BTU International, North Billerica, MA; ph 978/667.4111; sales@btu.com; www.btu.com.

Firing systems for solar cell metallization

The RFS and RFS-D fast firing systems for crystalline solar cell metallization feature transport speeds up to 6m/minute and multiple lanes and flexible transport systems that enable single-, dual-, and triple-lane handling of wafers with low breakage rate and high throughput (up to 5700 pcs/h at triple-lane transport). Features include an integrated residue management system, profile control, and process monitoring.

Rehm Thermal Systems, Blaubeuren, Germany; ph 49/7344.9606.0, info@rehm-group.com, www.rehm-group.com.

Converter modules for "parallel" solar installs

The vBoost converters (250W and 350W) can cut total system costs by 5%-10% by eliminating much of those BOS components—e.g., by integrating wiring and snap-on connector, and with a distributed maximum power point tracking that keeps inverters within optimal ranges. This leads to simpler array designs, extended lifetimes, and 5%-30% better power harvesting, the company claims. The converter modules are the core of eIQ's Parallux system, which can connect many PV solar panels on one cable—for example, a 20-fold improvement over conventional string architecture for hooking up thin-film panel arrays.

eIQ Energy, San Jose, CA; ph 408/533.8560, mlamb@eiqenergy.com, www.eiqenergy.com.

Encapsulation and potting materials

The insulating sheet comprises a silicone-organo copolymer that can be processed without curing or chemical reactions, offering elasticity and flexibility across a large temperature range to compensate for different CTEs of laminate materials. It is compatible with vacuum laminators and roll-to-roll processes for both crystalline and thin-film modules. The Elastosil Solar 2012 silicon elastomer encapsulant uses UV light to trigger crosslinking, enabling shorter curing times at room temperature without additional heat for thicknesses of several centimeters. The Elastosil 3210 two-part rubber material for concentrated PV high-performance modules is suited for the production of optical lenses and moldings, e.g. Fresnel lenses, with medium hardness (~45 Shore).

Wacker, Munich, Germany; ph 49/89.6279.1601, florian.degenhart@wacker.com, www.wacker.com

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LASTRAYS

Module pricing: Rational, or just plain nuts?

Paula Mints, *Navigant Consulting, Palo Alto, CA USA;*

In 2009, the market for solar products continued to soften, and by September, prices had crashed by 32% to 42%. This was great for the system integrators and installers who could source cheaper modules, (hard to resist at these prices!), but not so good for technology manufacturers who experienced squeezed margins and downward sloping revenues. (In fairness, system integrators have felt pressure to provide ever-lower system prices.)

2006 was a particularly auspicious year for price increases, with average module prices rising by 30% for the small buyers, 7% for mid-range buyers, and 12% for large-quantity buyers. The significant turnaround in pricing of 2009—which could be described as an overcorrection—does not mean that an efficient market price was arrived at. Rather simply, the market was willing to pay more at one point than it was at another.

In 2009, soft demand because of the loss of a major market (Spain), a global recession, and problematic debt markets (among other reasons) drove prices down, while significant levels of inventory on the demand side allowed a vibrant secondary market to develop. Suddenly, there were daily, always-downward pricing changes. The global market for cells and modules pseudo-corrected because it crashed—not a healthy situation for anyone.

On the manufacturer side (supply), the module business was unprofitable for more than 30 years, up until the boom; average pricing during some of these years was below cost. During the boom, margins swelled along with profit, and the industry behaved as if the party would never end.

The PV industry remains in start-up mode with applications, business models, marketing strategies, and technologies continuing to mature. As the high-growth grid connected application remains incentive-driven, it is hard to drape solid economic theory over industry pricing behavior. Moore's Law (the doubling of transistors per square inch on an integrated circuit doubles every 12 to 18 months) does not apply perfectly to pricing. Over the long term—and only in the long-term—there is clearly a systematic reduction in the price of cells and modules. In the near- to medium-term, though, there are many hiccups (up and down) in cell and module prices, and a smooth line cannot be observed. Until there is true, un-incentivized pull in the market for solar products, wild swings in demand and pricing will continue.

Efficient market theory holds that the market will establish (with the occasional correction) a rational and correct price for a good. This is great in theory; however, the market is an organism that reacts to market pressures by often inflating prices (supply side) when market conditions are good, and madly deflating them when market conditions turn in the other direction. It does this for any good, often regardless of its manufacturing cost.

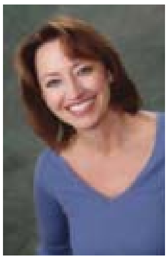
With easy access to information these days, the overload of constant module price updates can and does trigger much anxiety. Market drives price, and also value, and people are the market. Understanding this does not exactly help manufacturers ameliorate pricing anxiety, particularly when all around prices can be observed dropping like stones into a pond.

So, accepting that the market is not logical or efficient when it comes to pricing, what does this mean for solar? It means that there are no set rules for market pricing, but some understanding of the triggers might slow panicked selling.

In the case of cost reduction, the PV industry can be proud of the significant progress it has made in reducing manufacturing cost and increasing efficiency. In this arena, there is some logic—and in an industry with downward price pressure (live by the incentive, die by the incentive), lower costs are a necessity.

Lowering costs. Now there is a rational war worth fighting. ⊙

(This article appears in its entirety at: www.electroiq.com)



Paula Mints is principal analyst, PV Services Program, and associate director in the energy practice at Navigant Consulting, Palo Alto, CA USA; pmints@navigantconsulting.com

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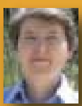

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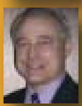

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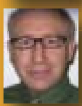

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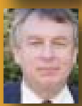

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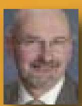

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