Module technologies for high-efficiency solar cells: The move away from powerful engines in old-fashioned car bodies

Joris Libal, **Andreas Schneider**, **Andreas Halm** & **Radovan Kopecek**, ISC Konstanz, Konstanz, Germany

ABSTRACT

Why change a product which can be sold in high quantities with a large margin? This is one of the reasons why crystalline silicon modules look the same today as they did 30 years ago. In addition, a module has to last for more than 20 years; to change the technology, or even just the material, many complicated, long-lasting and costly tests are necessary. And even after a series of successful tests there is no guarantee of a long-lasting product. Moreover, during the PV crisis starting in 2009, module manufacturers did not have the manpower and budget for introducing novelties into the module market. All the above are reasons why module architecture and materials did not significantly change with time and did not adapt to the introduction of powerful, highly efficient solar cells. After the crisis, however, many module manufacturers became aware that in order to be able to sell modules on the market with a high margin, their products not only have to be cost effective but also must differentiate themselves from the mass product. Consequently high-power, optically nice, colourful, back-contact, transparent, bifacial, light and highly durable modules are now being developed and are gradually being introduced into today's market. This paper reports on current trends and discusses future developments.

Introduction

As part of continuous efforts in the PV industry to further drive down the total cost of PV-generated electricity (the levelized cost of energy – LCOE), more and more cost-effective high-efficiency cell concepts are in the process of being implemented in the manufacturing lines of various solar cell producers. The following are just a few of these innovations: n-type metal wrap-through (MWT) at Yingli [1]; p-type MWT at JA Solar [2]; p-type passivated emitter rear cell (PERC) at many large solar cell manufacturers; and n-type passivated emitter, rear totally diffused (PERT), or BiSoN, at MegaCell [3]. Because of the new technological features of these cell concepts and their continuously decreasing manufacturing cost, the development and adoption of innovative technologies in the field of module assembly and related materials is essential, and motivates module

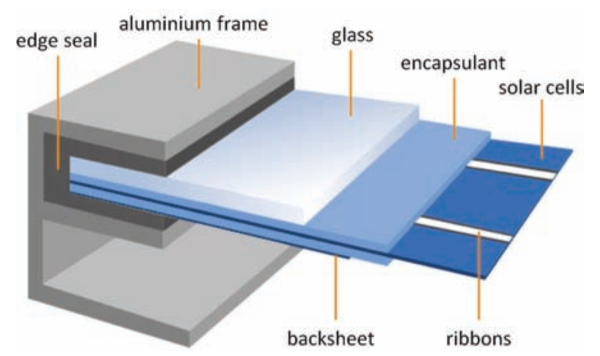


Figure 1. Cross section of a standard module.

	Current status 2014	Expected for 2018
Cell technology		
Average cell thickness [µm]	180	150
Back-contact market share	5%	12%
n-type market share	5%	20%
Module technology		
Average module glass thickness [mm]	3.2	2
Glass–glass module market share	5%	20%
Cell-to-module Pmpp losses multi cells	0–1% loss	1.5% gain
Cell-to-module Pmpp losses mono cells	>3% loss	0%

Table 1. PV industry expectations according to the latest edition of the ITRPV [4].

manufacturers to gradually move away from today's standard module design (see Fig. 1).

These new module technologies must have the following characteristics:

- Transfer a maximum fraction of the cell power to the module (i.e. exhibit low cell-to-module Pmpp losses).
- Guarantee an extended module lifetime and stable performance for 30–40 years.
- Contribute to a further cost reduction of the PV modules in €/Wp and – even more importantly – of the LCOE in €/kWh.

> “The development and adoption of innovative technologies in the field of module assembly and related materials is essential.”

In addition, new types of module that feature a significantly reduced weight, a frameless design or even bifacial energy conversion will contribute to a reduction in the PV system cost by significant savings in the balance of system (BOS) cost.

The latest edition of the International Technology Roadmap for PV [4] gives some interesting insights concerning the technological achievements that are expected by the PV industry in the future. Since the focus in this paper is on the near future, Table 1 lists the technological developments that are expected to be implemented by 2018 compared with the current status.

The following sections will give an overview of innovative technologies that are ready to be implemented in industry and that will contribute to fulfilling the expectations listed in Table 1. In this context, new materials – such as conductive adhesives (replacing soldering), alternative encapsulant materials and new backsheets (e.g. conductive backsheets for back-contact cells) – that are in the process of being introduced in industrial PV module manufacturing will be discussed.

Electrically conductive adhesives for thin cells and high durability of modules

Compared with the well-established soldering process, electrically conductive adhesives (ECAs) offer major advantages in solar cell interconnection, including:

- Bow is strongly reduced because of reduced process temperatures.
- Solar cells without front busbars can be contacted by means of adhesive (hence offering huge savings potential as regards Ag paste usage for cell metallization).
- Lead-free ribbons can be used, which is currently rarely the case because of the necessary 50K increase in soldering temperature, leading to increased cell breakage.
- Problems are avoided with the soldering process during cell interconnection of certain high-efficiency cell designs, such as rear-contact solar cells (e.g. the interdigitated back contact – IBC – cell design).

Recently, stringer equipment suppliers released new stringer generations for which the gluing process is adapted and modified (see Osborne [5] and teamtechnik [6], for example). Other suppliers are in the process of developing new stringers or modifications for existing equipment to adapt it to the glue application (dispensing or printing) and curing process.

Particularly because the entry into the market of new, highly efficient cell designs – such as IBC cells – is on the increase, the conductive adhesive technique promises significant advantages compared with soldering. This development coincides with a substantial reduction in the price of conductive adhesives, because of recent product developments, generally with fewer silver particles or alternative conductive materials in the adhesive. Conductive adhesive suppliers have recently developed new products which demonstrate increased conductivity and bonding strength to the solar cells, thereby eliminating two of the major disadvantages associated with conductive adhesives: their low bonding strength in the range of 0.5–1.5N and significantly higher cell-to-module losses than for cells interconnected by soldering.

With the new adhesives and stringer systems, a real alternative to the soldering process for interconnection now exists, providing potential customers with quality and reliability which are comparable – or even superior – to what they received from systems based on soldering. Fig. 2 shows the excellent performance of modules where gluing of Cu ribbons has been used for the interconnection of two-side contacted cells: when combined with a suitable encapsulant (EVA for example), the tested modules exhibited less than 1% Pmpp loss after 3000h of damp-heat testing [7]. In addition, it has been shown that this type of module configuration also resists very well thermal-cycling tests with up to 600 cycles [8].

Cell encapsulation

The cell encapsulation material – such as EVA, which for decades has been the main material used in industry – is one of the key materials in solar module

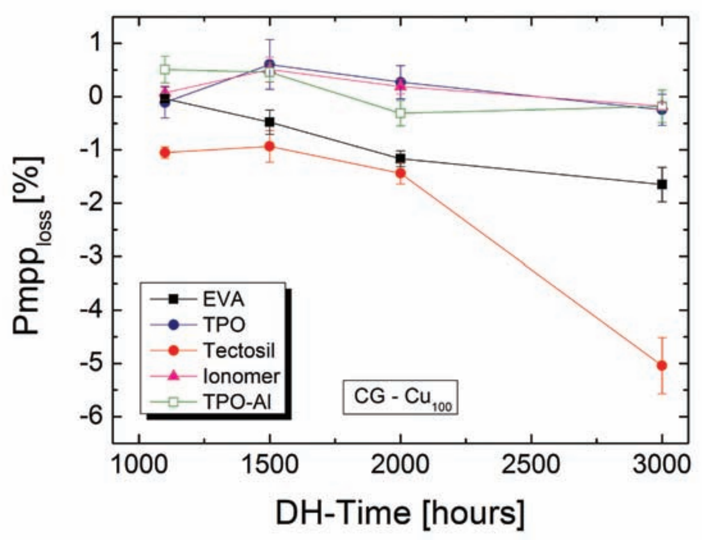


Figure 2. Pmpp loss after climate chamber testing for modules with (two-side contacted) standard cells interconnected using copper ribbons that have been glued with conductive adhesive. Choosing a suitable encapsulant enables very good reliability to be achieved, even after 3000h of damp-heat testing [7].

processing. On the one hand, it has to be highly transparent to allow as much incident sunlight as possible to reach the cell surface, thus keeping the cell-to-module losses low. On the other hand, the material has to demonstrate strong adhesive bonding to the solar cells, glass and backsheet in order to resist UV irradiation, environmental factors (such as acid rain and ammonia gases) and permanent temperature cycles with large peaks at lower and higher temperatures.

The first key performance indicator (KPI) is typically established by measuring the cell-to-module losses, whereas the second is determined during thorough climatic tests and exposure to UV light. Only recently, the encapsulation material was found to be one of the key materials in preventing potential-induced degradation (PID) [9], hence leading to a strong push towards the development of encapsulation materials with very small water diffusion and storage and high volume resistance. Another crucial aspect is the development of highly efficient solar cell technologies that demonstrate a strong spectral response in the blue wavelength. Such a characteristic requires encapsulation materials which exhibit sufficient transparency at lower light wavelengths but, at the same time, do not jeopardize either the bonding strength to other materials or the long-term stability, both of which are subject to degradation by UV radiation.

Besides NICE module technology by Apollon (requiring no encapsulant at all – see the discussion later in this paper), all high-efficiency solar cell concepts – in particular those based on n-type wafers – have two important requirements with respect to the encapsulant. First, the encapsulant has to be chemically compatible with the metal pastes used for cell fabrication as well as with the conductive adhesive. Second, many advanced cell concepts, especially IBC cells, feature an excellent spectral response in the short-wavelength range (300–400nm). In order to transfer this efficiency increase to the final module, highly UV-transparent encapsulants are necessary. Promising candidates for meeting these requirements are ionomers, polyolefines, liquid silicone and recent newly developed EVA products. Moreover, certain polyolefines have demonstrated a resistance to PID, for example when used in modules incorporating Zebra cells [10]. When considering back-contact cells, the front-side encapsulant can in any case be thinner than that for standard modules, leading to an increase in light transmission and hence significantly reducing the costs.

Very thin module glass for low-weight glass–glass modules

The standard thickness of solar glass used in the PV industry for the construction of PV modules has gone down steadily over the last few years. In 2008 the industry switched from a 4mm-thick glass to 3.2mm, and we are now looking at another thickness reduction in the near future from 3.2mm to 2mm, or even 1.5mm.

> “Glass–glass PV modules have significant advantages in terms of mounting, since no metal frame is required.”

Because of its considerably reduced weight, glass of 2mm and below offers the important advantage of the production of glass–glass modules with the superior characteristics of such glass. In general, glass–glass PV modules have significant advantages in terms of mounting, since no metal frame is required. The heavy weight of glass–glass modules using 4mm or 3.2mm glass was the main factor that prevented industry from supplying this extraordinary product to the market. The thickness reduction is accompanied by an improved light transmission, hence reducing the cell-to-module Pmpp losses. Another advantage is the increased durability, since, in contrast to foil backsheets, no water at all can penetrate the solar module interior (except for a small fraction at the edge region of a module, which applies to any module technique).

Thin glass significantly increases the flexibility of glass–glass PV modules. The strong mechanical resistance and flexibility of tempered thin glass allows the processing of extremely lightweight glass–glass PV modules. With a thickness of both the front- and back-side glass of 2mm and below, glass–glass modules are remarkably efficient and diffusion-proof. This is true not only for water but also for ammonia gases, which are fully blocked by the glass and cannot damage the module interior. Furthermore, this module technology does not require any metal frames, which saves on materials and weight. The reduced weight of thin glass–glass modules opens up new markets, such as building-integrated photovoltaics (BIPV) products or bifacial solar modules. The excellent flexibility of glass–glass modules makes this product mechanically very robust, even under large loads. One advantage here is that the solar cells are placed in the neutral zone of the module, thus reducing the effective mechanical stress imposed on the solar cell to a minimum when a mechanical load is applied to the module.

In short, by taking the glass–glass module approach, it is possible to solve many of the problems typically observed with standard backsheet PV modules, such as low light transmission (hence high cell-to-module losses), poor flexibility and unsatisfactory durability.

Liquid silicone

Because of its excellent and stable optical properties, as well as its chemical stability, silicone was a common encapsulant material for c-Si PV modules in the 1970s and early 1980s. Since at this time silicone was rather costly, and the related processing technology was not compatible with high-volume production of PV modules, it was rapidly forced out of the market by EVA.

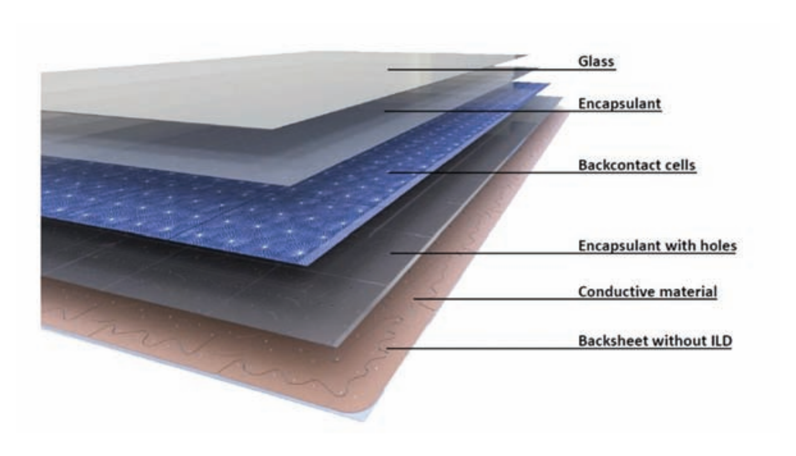
In recent years, new silicone formulations – specially adapted to the requirements of PV – have been developed, along with process technologies that enable low-cost and high-volume production of PV modules (e.g. Dow Corning/Reis and Momentive/Kuka). Compared with EVA, from the point of view of processing, liquid silicone encapsulants enable short cycle times and reduced process temperatures (curing within several minutes at around 80°C). With the optimum silicone formulation, this type of liquid encapsulant features a number of advantages, such as high light transmission in the wavelength range of 300 to 400nm [11] and the capability of suppressing PID effects considerably [12].

Being much more resistant to yellowing after UV exposure than EVA, as well as retaining much less humidity, silicone encapsulants promise very low degradation rates for PV modules; these encapsulants will therefore contribute to achieving module lifetimes of more than 30 years, particularly if they are integrated in a glass–glass module design, in which the traditional backsheet materials are replaced by a thin glass sheet.

All the characteristics mentioned above are gaining more importance with the increased demand for the installation of modules in regions with harsh climatic conditions, such as deserts in, for example, the MENA region and South America (see also

Source: Meyer Burger.

Figure 3. Schematic representation of SmartWire technology, showing the metal fingers of a single cell contacted with smart wires.



Source: Eurotron.

Figure 4. Cross section of an MWT module constructed with conductive backsheet technology.

the 'Development of desert modules' section later in this paper).

SmartWire approach

SmartWire Connection Technology (SWCT) (see Söderström et al. [13], for example) – formerly called *Day4Energy Electrode* – is a novel module technology which has been further developed and distributed by Meyer Burger. This technology is based on an electrode in which metal wires are retained in an adhesive film, and replaces the conventional solar ribbon (see Fig. 3). In contrast with soldering, SWCT involves a low-temperature process, resulting in a significant improvement in efficiency and reducing the negative effects of micro-crack generation by thermomechanical stress typically seen with soldering at high temperatures.

The wire matrix generates more than 2000 contact points between the solar cell and the wires: the solar cell therefore exhibits a significantly higher efficiency and reliability in terms of electrical contact. Meyer Burger states that in comparison with conventional three-busbar technology, SWCT results in a reduction in Pmpp losses by 3% for solar cells after encapsulation in the module. Because of the reflections from the wires in the SWCT design, the effective shading on the solar cells is only 70% of the wire diameter. The large number of contact points leads to excellent performance, as observed in extended climatic tests. A broken metal finger or chipped or cracked solar cell usually means a loss in electrical connection, resulting in significant electrical losses. In the case of SWCT, each finger is electrically contacted to the matrix of wires, which serves as a backup for the electrical contact: therefore even cells with micro-cracks or broken cells exhibit little or no loss in performance, yielding a 1% increase in production, according to Meyer Burger.

Another noteworthy advantage of SWCT technology is the price reduction realized in the solar cell process, since this technology does not require busbars, and significant economies are made on the amount of silver paste used during the cell process. It is also worthy of mention that SWCT technology facilitates the interconnection of high-efficiency cell designs for which currently no, or only non-optimized, interconnection technologies exist. For example, heterojunction solar cells combined with SWCT can be interconnected in a reliable way, yielding the lowest cell-to-module Pmpp losses.

Back-contact modules based on a conductive backsheet

One new approach used in module assembly which breaks away completely from the tabbing-stringing technology is the conductive backsheet (CBS) technique. This method was adopted from printed-circuit board production and is only suited to back-contact cells. It was developed by TTA and ECN for p-type MWT solar cells and was introduced to the market in 2009 by Eurotron, a daughter company of TTA. Other providers of technology and equipment for module assembly based on CBS are the Finnish company Cencorp and the Italian company Formula E.

The typical module sandwich including CBS (see Fig. 4) is composed of glass, front encapsulant, back-contact cells, rear encapsulant with local openings to contact the cells, and the conductive backsheet, including a polyethylene terephthalate (PET) and Tedlar or similar layer on the rear. The metal layer, which is the basis of each type of CBS, is around 35µm thick (depending on the supplier), making its total mass on the area of a solar cell more than twice the mass of ribbon (2 × 0.2mm) needed to interconnect a three-busbar cell. This results in very low series-resistance-related Pmpp cell-to-module losses.

The CBS is mostly made from copper or aluminium coated with a thin layer of copper to aid contacting (e.g. Hanita Coatings' DuraShield). The metal covers nearly the whole module area and is only interrupted by small isolating trenches, which define conduction paths for both polarities.

Initially, structuring of the metal layer was solely realized by wet chemical processes; nowadays, cheaper and simpler structuring tools based on laser or mechanical milling are gaining popularity. The copper layer is finished with, for example, ZnCr (e.g. Krempel's AKACON BCF) or treated with an organic surface protectant (OSP) on the side (e.g. Isovoltaic's Icosolar TPC 3480) facing the solar cells to avoid corrosion. For most CBS concepts the rear encapsulant provides electrical isolation between the CBS and the cell. The encapsulant is locally opened by mechanical punching or laser.

These types of backsheet also include a stack of PET and Tedlar (or similar material) on the rear side to protect against environmental influences. Other concepts, such as 'contacfoil-connect' by Eppstein Technologies, use a polyvinyl butyral (PVB) layer on top of the Cu for electrical isolation. This PVB layer is locally ablated by laser to allow contacting. In module assembly, the rear encapsulant is placed behind the CBS, followed by a standard backsheet or Eppstein's 'contacfoil-back'. The EBfoil BYS developed by EBfoil and produced by Coveme is a stack system consisting of an encapsulant with a dielectric interlayer combined with a conductive backsheet composed of PET layers, a copper or aluminium conductive layer and a primer layer. After structuring the two components according to the desired module circuit design, both sheets are pre-tagged by dedicated Formula E equipment and can be handled within the module assembly line by Formula E as one single sheet combining the CBS and the rear-side encapsulant.

The interconnection of a back-contacted solar cell using a CBS is accomplished by ECAs, solder paste or laser soldering. Laser soldering is performed after module lamination, whereas ECAs and solder paste are applied locally onto the CBS by stencil printing or dispensing during module assembly. The printing image matches the openings in the isolation layer to allow contact formation. Back-contact cells are precisely placed on top of the rear module stack using a pick-and-place unit, which subjects the cell to very low mechanical stresses compared with soldering. Usually, after cell placing the finished sandwich is flipped before lamination. During lamination, ECA or solder paste is cured and establishes the contact between the cell and the CBS while they are enclosed by the insulating layer; this is the reason why no electroluminescence (EL) inspection of modules prior to lamination is possible.

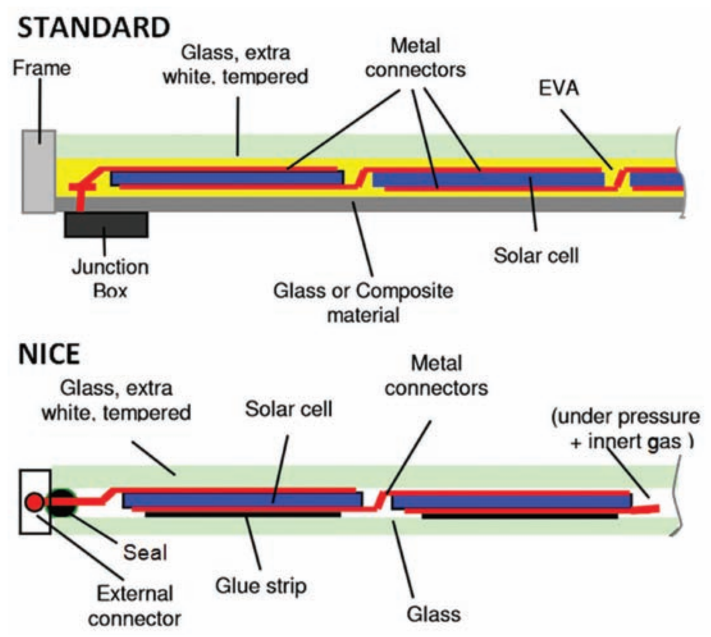


Figure 5. Standard module technology (top) compared with NICE technology (bottom) (image from Dupuis [14]).

Back-contact module assembly by tabbing–stringing

The traditional way of assembling back-contact modules is the single-sided tabbing–stringing procedure. Dedicated equipment for 6" cells with several (up to eight) rear busbars is offered on the market by different companies (e.g. Komax Solar, teamtechnik and Meyer Burger) and is already in use for the production of MWT modules. The contact between the cell and the ribbon can be realized by soldering or ECA gluing. For MWT, only point contacts between the cell and the ribbon are possible; an isolation layer has to be introduced locally to separate the ribbon and the cell. This isolation is not needed for IBC cells, such as the Zebra cell, featuring a floating busbar structure on the rear, and soldering on the full length of the busbar can be achieved. Single-sided ribbon interconnection imposes high mechanical stresses on the solar cell, impacting only from one plane, which is why either structured or super-soft ribbon is used to minimize bowing.

> "Single-sided ribbon interconnection imposes high mechanical stresses on the solar cell."

An important advantage of a ribbon interconnection compared with a CBS is the possibility of constructing a bifacial module by either using a transparent backsheet or assembling a glass–glass module. In this case the bifaciality of rear-contacted cells, like the Zebra cell, can also be exploited at the module level, leading to a significantly increased energy yield (kWh/kWp(front)) and hence a reduced LCOE (€/kWh).

NICE module technology

Apollon Solar has developed a novel industrial PV module technology under the acronym NICE, standing for 'new industrial cells encapsulation' [14]. The key elements of this module technology (Fig. 5) are:

- The electrical series connection between the solar cell contacts and the metal interconnectors is soldering free. Contact is obtained by creating and maintaining a lower pressure inside the module, which establishes a pressure contact between the solar cell contact terminals and the metal interconnectors.
- The NICE module is sealed by a polyisobutylene (PIB) edge seal that also provides the mechanical contact between the module front glass and rear glass, as well as acting as a barrier to moisture and air ingress. The inner volume of a NICE module is filled with a neutral gas to protect the module components from oxidation.
- The absence of lamination and soldering for the cell interconnection in NICE module technology for

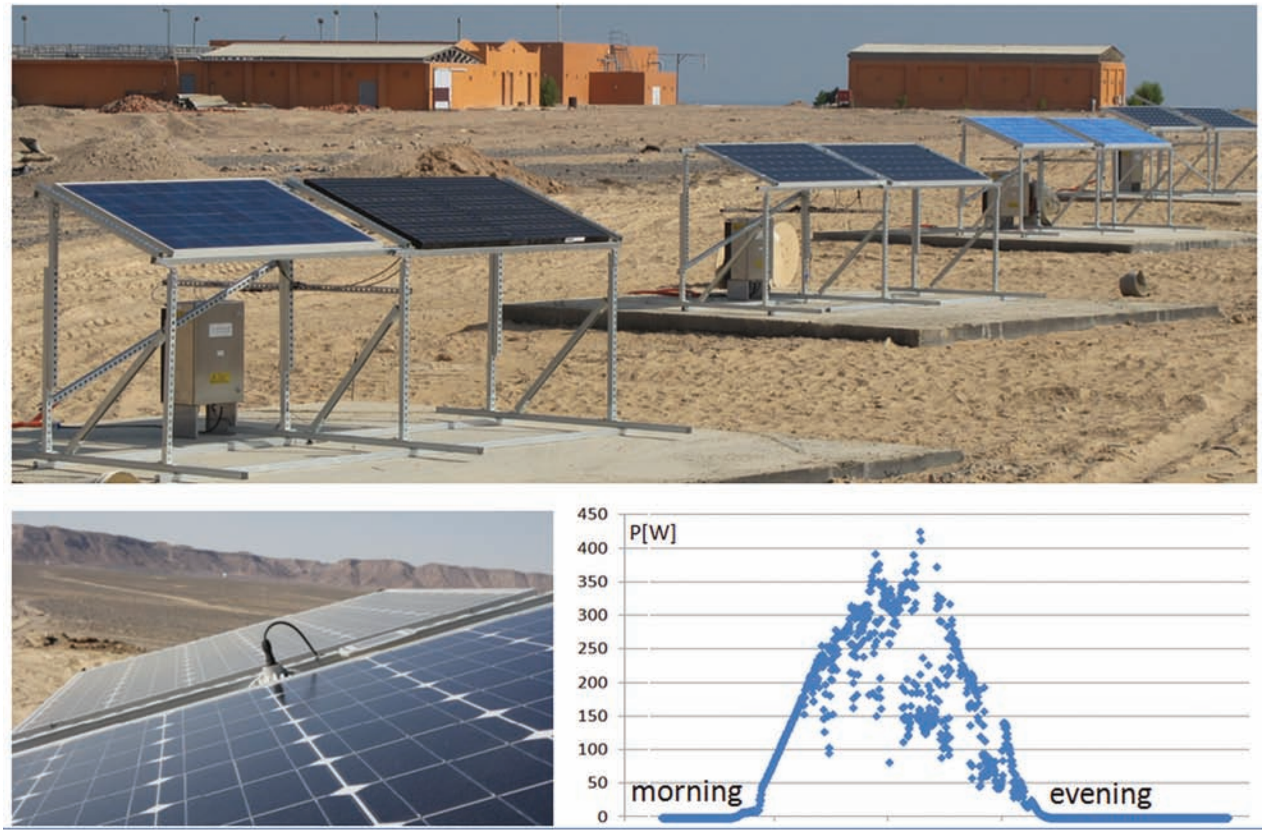


Figure 6. Measurement set-ups for standard and bifacial modules under desert conditions in el Gouna, Egypt. A peak power of around 450W was measured for the non-optimized bifacial BOSCH module (see graph).

solar cell encapsulation simplifies the recycling of modules, because they can be easily disassembled and separated into their different components: glass, copper interconnectors and cells.

As NICE is a glass–glass technology it can be used for bifacial applications. Production of 40MW NICE modules is already in operation in Tunisia and is currently set up in Algeria.

Development of desert modules

In the past, the modules have been developed for the European market, as this technology was cost effective only with feed-in tariff schemes: all the properties and testing, therefore, were adapted to conditions in Europe. The modules have to withstand, for example, strong hailstorms and heavy wind and snow loads. However, now that the technology is so cost effective even without any subsidies, it can be deployed with grid parity in many regions, such as desert areas. Consequently other testing conditions and module properties are crucial in order to ensure that modules will withstand a harsh desert environment. In addition, all deserts are not the same and conditions in, for example, the Atacama region are different from those in the Sahara, different properties for the modules are essential. In the Atacama Desert high UV irradiation and powder-like sand are present, while in the Sahara very high temperatures and powerful sandstorms attack module stability. The material used must therefore be inert to abrasion and withstand high temperatures. In addition the module efficiency must remain high, even at high temperatures, which makes the use of solar cells with a low temperature coefficient necessary. Such cells require high voltage, for example PERC cells using solar-grade (SoG) mc-Si wafers [15] in the case of multicrystalline cells, or n-type solar cells in the case of Cz cells. Since development is leaning towards glass–glass modules anyway, and high reflectivity is present in desert areas, it makes sense to use bifacial modules. To summarize, a module for desert conditions will have the following properties:

- glass–glass module
- glass with coatings that protect against, for example, soiling and abrasion
- solar cells with high voltage
- bifacial solar cells
- half cells for improved fill factor (*FF*), enabling the use of standard bypass diodes

Fig. 6 shows a test field in el Gouna (Egypt), where such modules with different architectures are deployed. For an n-type BOSCH module with a front power of 300Wp, a record 'effective power' (We) of close to 450Wp has been achieved.

> "The future of desert systems belongs to bifacial glass–glass modules."

With a real system, of course, there will be more shadowing than with an almost free-standing module. However, compared with monofacial systems, yearly increased electricity productions of 10–25% (depending on albedo, module technology, system set-up and the ratio of diffuse irradiation to direct irradiation) have already been reported from bifacial systems. The authors are sure that the future of desert systems belongs to bifacial glass–glass modules, which yield a longer system lifetime as well as greater electricity production, thus reducing the cost per kWh. Bifaciality in general will gain in importance, as can be witnessed, for instance, in the set-up of the bifacial solar cell factories of MegaCell in Italy and Mission Solar Energy in the USA.

(A follow-up article dealing with the topic of bifaciality is planned for a future issue of *PV International*.)

Summary and outlook

This paper has summarized (without claiming to be comprehensive) future module technologies, which will be introduced to the PV market at an increasing rate. The authors believe that the PV market will develop similarly to the car industry, where adapted versions of the standard product will be used for different regions and different 'occasions', even if the functions of a module remain the same, namely to live long, to produce plenty of electricity (low cost per kWh) during that lifetime, and, in some cases, to also look good.

In addition, the electric car and PV industries currently have one more thing in common: in order to reach the full potential of both technologies, better and more cost-effective batteries need to be developed.

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About the Authors

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

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

Andreas Halm studied physics at the University of Konstanz and completed his diploma, with a thesis topic of nanomechanics and nano-optics. Since June 2008 he has been working as a project manager at ISC Konstanz, specializing in solar cells made of SoG silicon. He has also been heavily involved in the development of high-efficiency back-contacted n-type silicon solar cells since the beginning of 2010.

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

Enquiries

ISC Konstanz
Rudolf-Diesel-Straße 15
78467 Konstanz
Germany

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