Half-cell solar modules: The new standard in PV production?

Jens Schneider, Hamed Hanifi, David Dassler, Matthias Pander, Felix Kaule & Marko Turek, Fraunhofer Center for Silicon Photovoltaics CSP, Halle (Saale), Germany

Abstract

Solar modules with half-size solar cells have the potential for becoming the new standard. The cutting of cells leads to electrical recombination losses at the cell level, which are more than compensated by reduced resistive losses as well as by current gains at the module level. At the same time, the cutting process must be optimized to avoid mechanical damage that could lead to cell breakage in the module. Module design opportunities for hot-spot protection, shading resistance and energy yield optimization are presented in this paper. Module power can be increased by 5–8%, which justifies the investment in additional equipment for cell cutting, stringing, lay-up and bussing. Half-cell technology is highly attractive for new solar module production capacity.

Motivation

An increasing number of solar module producers offer half-cell solar modules. According to ITRPV 2018 [1], the market share of half-cell solar modules is expected to be close to 40% in ten years' time. But why are half-cell modules becoming more relevant now? How large is the performance benefit and what investment is required? What is important to keep in mind and what side effects can be expected? This paper presents an overview of half-cell solar modules.

In general, half-cell modules generate higher power and energy yield through the reduction in electrical losses. Electrical losses in solar cell interconnections increase with the square of the electrical current, as defined by Ohm's law. Cutting the cells in half cuts the current in half, and the electrical losses are reduced to one quarter of the full-cell losses [2,3]. It is important to note that only series resistance losses in the cell tabs are affected. Series resistance losses at the cell level are not reduced, since the series resistance of an individual half cell is twice the resistance of a full cell, while, at the same time, the number of cells in the module is doubled, offsetting all benefits.

Why are half-cell modules only now attracting increasing interest? One reason is that the increase in solar wafer and cell size from 156mm (M1) to 161.7mm (M4) in wafer length increases the cell area and current by about 7%, and thus the electrical losses by 15%; this has stimulated the interest in current-related loss reduction. The reduced shading from cell metallization and the increase in the number of busbars also further increase cell currents. Moreover, improvements in wafer and cell process uniformity allow the sorting of full cells, rather than remeasuring half cells after cutting, which decreases the amount of work associated with half-cell modules. Half-cell modules will be discussed next in more detail.

Cell cutting technologies

All commercially available silicon solar cells of half-cell dimension are produced in a two-step production process. First, the standard full-size solar cells are manufactured; there is no change in the processing required, except for a possible adaptation of the metallization layout. In a second step, the half-cell cutting process takes place, for which there are two major technological approaches available: laser scribing and (subsequent) cleavage (LSC) and thermomechanical-induced cell separation (TMC).

The first approach – LSC – relies on a laser ablation process, creating a full-length scribe along the half-cell edge. In some cases, this scribe does not yet fully separate the cell, but results in a groove with a depth of about one half of the cell's thickness. Subsequently, a mechanical breakage of the cell occurs, which is guided by the laser scribe. Since the laser process causes some structural damage to the material [4], the scribing is typically performed from the back side in order to avoid a shunting of the p-n junction; in this case, the laser process can be employed in a more efficient manner if there is a small gap in the rear-side metallization. For passivated emitter and rear contact (PERC) solar cells with a full-area rear-side passivation, such a gap in the rear-side metallization does not lead to any power loss. At Fraunhofer CSP, a more advanced version of this LSC process has been developed and filed for patent. The Fraunhofer CSP version relies on the application of the laser process to a slightly bent solar cell; this mechanical preload results in a one-step process in which the laser scribing and breakage occur simultaneously within the same processing unit [5].

The second approach – TMC – is based on a non-ablative process, where a small crack is induced, which then propagates by imposing a highly localized thermal gradient on the material along the half-cell edge; this thermal gradient leads to some local mechanical stress within the cell, resulting in propagation of the crack. For this process, there are already some half-cell tools commercially available (or under development), for example from German laser tool suppliers 3D-Micromac AG or Innolas Solutions GmbH. As these TMC processes are ablation free and

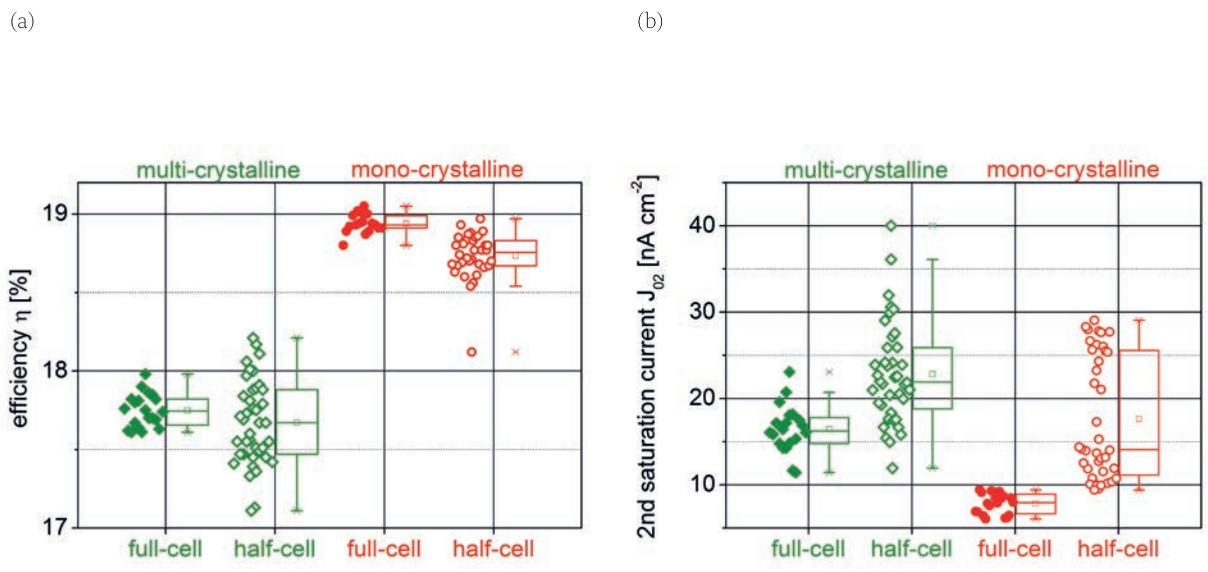

Figure 1. (a) Reduced cell efficiency resulting from the cutting process, caused by (b) the increase in the second saturation current density J_{02} [2].

have reduced total thermal impact, the structural damage can be decreased once an optimized set of process parameters has been determined.

Electrical properties

Two major quality issues must be considered with regard to the half-cell processing. First, the electrical losses due to the additional cell edge have to be minimized. Second, the mechanical strength, and thus the reliability, have to be maintained. As regards the electrical properties, it has been found that even an optimized half-cell process leads to some minor electrical losses of about $0.5\%_{rel.}$ in the cell, caused by some additional recombination processes at the half-cell edge [6–8]. This is reflected in an increase in the J_{02} current contribution to the current losses (see Fig. 1).

While the efficiency of a half cell is slightly reduced, this is more than compensated by the gains at the module level; these gains can be distinguished into three physical mechanisms. First, the reduced cell current leads to a reduction in series resistance losses in the cell tabs, to one quarter of the full-cell module losses. Depending on cell type, these losses can add up to about 3% of the module power and are reduced to 0.75%, i.e. by about 2.25%. The resulting power gain is related to a reduction in series resistance and an improvement in fill factor of the module.

Second, the increased number of cells also leads to an increased number of cell spaces. Via reflection from the backsheet, the cell spaces contribute to a gain in short-circuit current [9]. Although an increase in total cell spacing also leads to a larger module in general and a higher cost of materials, these parameters should be reoptimized when moving to half cells. When the cell spacing between half-cell and full-cell modules is kept constant, an increase in short-circuit current of up to 3% is found [3]. Optimization of

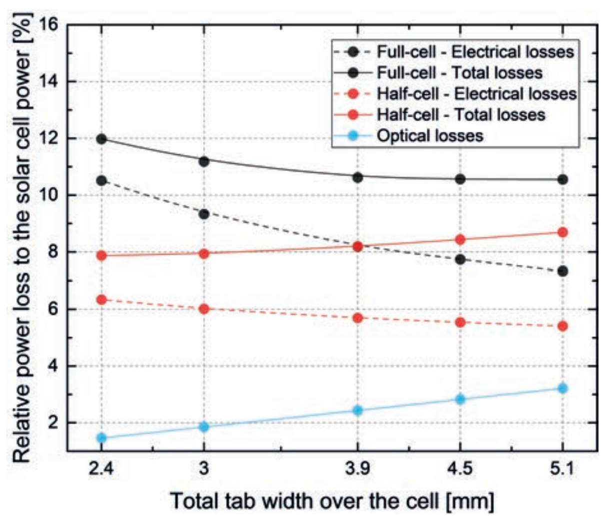

Figure 2. Electrical, optical and overall power loss of full-cell and half-cell mini-modules as a function of total tab width of all cell tabs, under standard test conditions (STC).

“While the efficiency of a half cell is slightly reduced, this is more than compensated by the gains at the module level.”

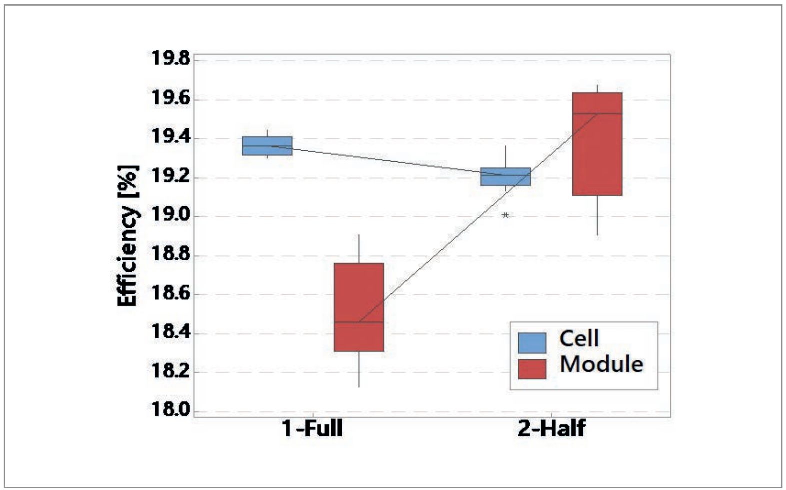

Figure 3. Solar cell and module efficiency for full cells and half cells. While half cells have slightly lower efficiency than full cells, the effect is far more than offset at the module level under STC [11].

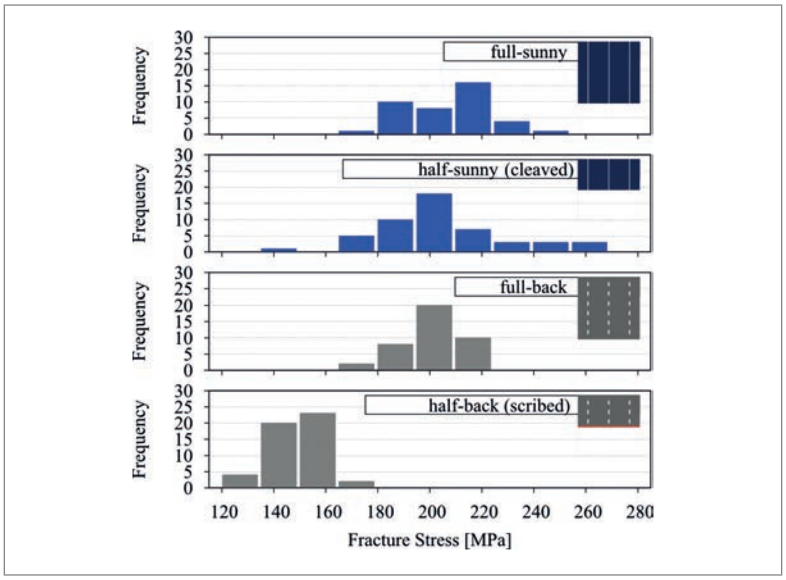

Figure 4. Results for cell breakage frequency of full- and half-size solar cells, with fracture stress applied to the cleaved sunny side and laser-scribed back side of the cells. Significantly lower fracture stresses are observed when the cells are stressed on the laser-scribed edges.

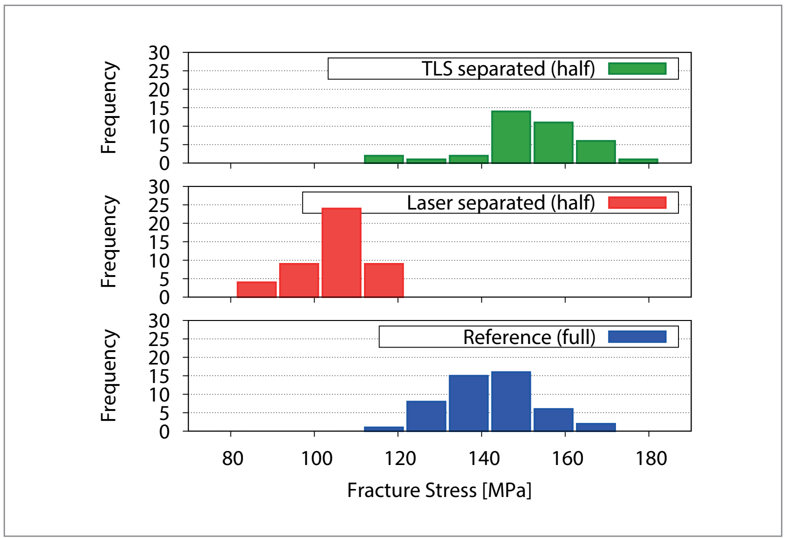

Figure 5. Results for cell breakage frequency of full-size reference and half-size solar cells cut by thermal laser separation (TLS) and by laser scribing and cleavage (LSC). The TLS process often results in no detectable damage to the half-size cells.

the module power and geometry can be nicely carried out using Fraunhofer ISE's Smart.Calc tool [10] (see also www.cell-to-module.com).

A third opportunity for improvement lies in reoptimizing the cell tab width. The cell tab cross section should be large in order to minimize electrical losses. While cell tab thickness is limited to about 200µm by mechanical properties (especially the impact on cell breakage), the width is optimized between reducing electrical losses with wider tabs and reducing optical shading losses with narrower tabs. When electrical losses are reduced, the optimum width obviously changes as well. Fig. 2 shows both optical and electrical losses of a single-cell full-cell mini-module and a comparable double-cell half-cell mini-module under standard test conditions (STC). The *optical losses* for both mini-modules are the same. The *electrical losses* in the half-cell mini-module, however, are less than those in the full-cell mini-module because of reduced current passing through the tabs. The optimized tab width for half cells based on total losses is around 0.8mm, which is about 50% of the optimized value of 1.7mm for a full-cell layout. As a result, the combined optical and electrical power loss is reduced from 10.5% to 8%, equating to 2.5%$_{rel.}$.

Thus, whereas the solar *cell* power is reduced by more than 0.5%$_{rel.}$, the solar *module* power is increased, more than offsetting all losses; this is demonstrated in Fig. 3, where cell and module efficiencies for full and half cells are shown (note: module efficiency is calculated using total cell area). From the graph, it is also clear that half-cell modules are able to increase the cell-to-module (CTM) power ratio to above 100% [10]: while the CTM ratio for a full cell is only 93%, the half-cell module has a CTM ratio of even 101%, compared with the full-cell efficiency reference. In other words, the half-cell module efficiency with optimized cell spacing and tab width is 8%$_{rel.}$ higher than the full-cell module efficiency.

Mechanical properties

The mechanical strength of the half cells is the key parameter affecting production yield and module reliability. Any reduction in mechanical cell strength leads to an increased breakage likelihood during the module operation in the field. The half cells have a lower characteristic strength than full cells. By testing cell strength from the sunny side and the back side (see Fig. 4), it was shown that the cells are mechanically damaged from the rear; thus, it is the laser scribing and not the cleaving that leads to mechanical damage.

The mechanical properties of the half cells depend, in a very subtle way, on the details of the half-cell processing and the mechanical full-cell properties. However, it has been found that TMC processes fairly generally lead to less mechanical damage than LSC approaches [6,8]. In Fig. 5, the

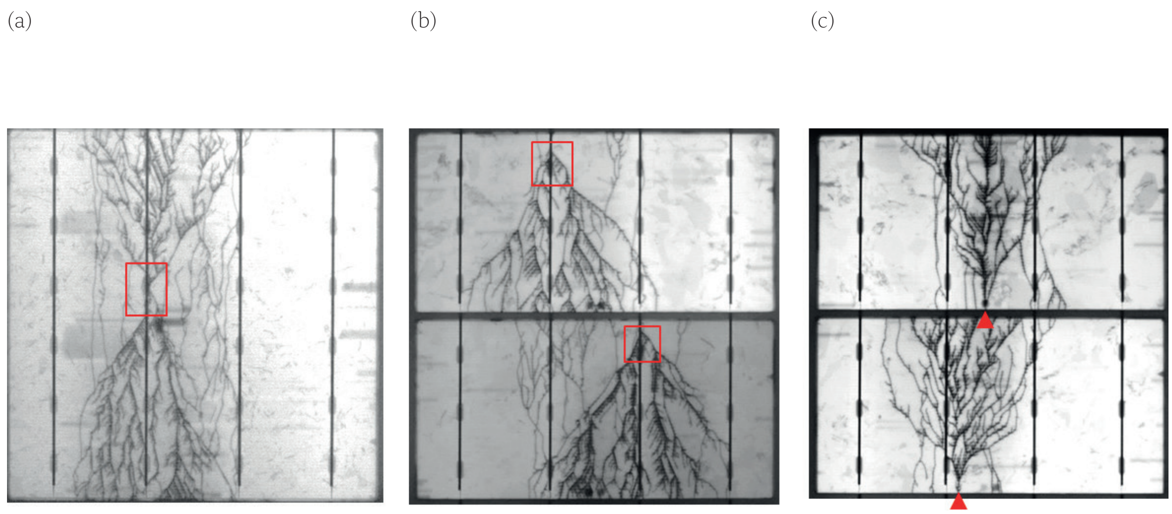

Figure 6. EL images (contrast and brightness adjusted) of broken cells from the module laminate fracture tests, with fracture origin (red square) at the busbars for (a) full cells and (b) TLS, and at the cutting edge for (c) LSC [8].

fracture stresses for cells with thermal laser separation (TLS), a type of TMC, and with LSC, and for reference cells are shown. The TLS process did not demonstrate any reduction in fracture stress; this means that it is possible to cut solar cells without incurring mechanical damage.

An increased failure rate of the solar cells is directly related to an increased failure of the cells within the modules [8]. In a four-point bending (4-PB) setup of solar modules with an in situ electroluminescence (EL) control [12], it was possible to show that half-size solar cells cut with the LSC process, and incorporated in a module laminate, are inclined to break at the laser-scribed and cleaved edge, while reference full cells, as well as half cells cut by an optimized TLS process, tend to break at the busbars; this can be seen in the EL images in Fig. 6, taken during the 4-PB experiment. Breakage of the LSC cells occurs at the laser edge at lower stresses, relevant to wind and snow loads. It is therefore particularly important to optimize and control the mechanical properties of the half cells after cutting, in order to avoid potential failure resulting from excessive cell breakage in the field.

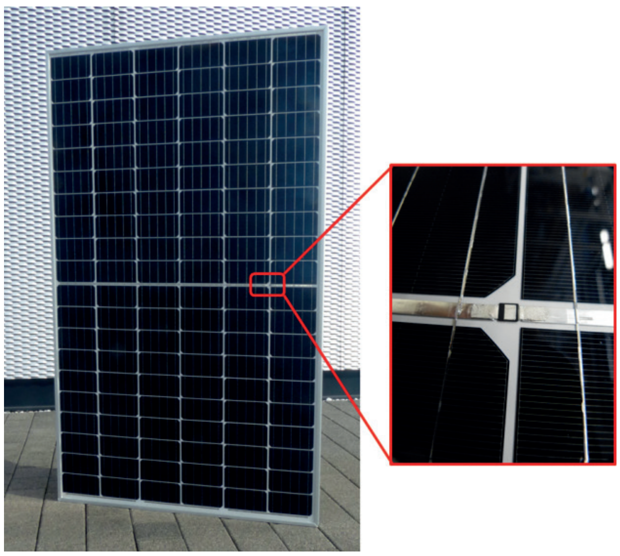

Figure 7. A half-cell module in the portrait layout, showing the integrated bypass diode, fabricated at Fraunhofer CSP.

Module redesign

Half-size cells mean that there are also twice the number of cells. To allow for bypass diodes to protect 20 to 24 cells from hotspots, module redesign is necessary, with two parallel strings on one bypass diode. At the same time, this has the advantage of similar current and voltage values compared with full-cell modules. There are two design options for half-cell modules: portrait and landscape, each with centralized or decentralized junction boxes.

Portrait design

In the portrait design, the module is divided into an upper and a lower block; each block has six substrings of 10 or 12 half cells connected in series. The upper and lower blocks are connected

“It is particularly important to optimize and control the mechanical properties of the half cells after cutting.”

in parallel, with bypass diodes protecting each of the parallel substrings.

Most commonly, half-cell modules are produced in the portrait design. BP Solar (BP3270T) started with 144 half cells, while Bosch Solar Energy (c-Si M60+ S) offered modules with 120 half cells with a centralized junction box. REC Solar offers their 'TwinPeak technology' half-cell module in the portrait design and decentralized junction boxes, which require fewer interconnecting ribbons inside the module and also require shorter cable sizes to connect the modules to the neighbouring modules. Fraunhofer CSP presented a portrait half-cell module with integrated bypass diodes inside the laminate (see Fig. 7). The integration of bypass diodes inside the laminate leads to a reduction in the number of distributed junction boxes from three to two, and to a decrease in material consumption.

Landscape design

Mitsubishi (PV-MLE Series) introduced a 120-half-cell module in the landscape design, while SERIS and Fraunhofer CSP presented a module with 144 half cells in a landscape design in 2013. The latter module has twelve substrings with twelve half cells, which are arranged in parallel two by two and then connected in series. The layout makes it possible to use the standard glass size for a 72-cell full-cell module. The module is aligned in a landscape orientation, and the junction box can be either centralized or decentralized and located on the top side of the module. The two-by-two interconnection of half-cell modules with a landscape layout makes them more resistant than the equivalent full-cell modules under partial shading conditions [3,13,14].

Energy yield

All previous considerations have been in relation to solar module *power* under STC, so a closer look will now need to be taken at *energy yield*. Three things to bear in mind regarding the energy yield of half-cell modules are:

1. Half-cell modules are more shading tolerant.
2. Benefits of half-cell modules very much depend on high insulation.
3. Lower losses in half-cell modules might allow them to operate at a slightly lower temperature.

In a full-cell layout, when a solar cell is being shaded and exceeding a specific shading percentage, the related string will be bypassed by the bypass diode. This process is dependent on the area of the solar cell being shaded, and the shading shape or direction is not relevant. On the other hand, half-cell modules with a landscape design exhibit a higher capacity to withstand partial shading conditions. The parallel interconnection of substrings in half-cell modules with a landscape design makes it possible to generate current in one substring while the other substring is partially shaded. This shading tolerance is highly dependent on the shading direction (or module orientation). In the case of the shade moving along the *y* axis and shading one half cell completely (equivalent to 50% shading of one full cell), one substring cannot generate current, whereas the other one still produces current. In the case where the shade moves along the *x* axis, after 50% shading of two half cells the affected substring still produces electrical current [13,14]. Fig. 8 shows the power–voltage curves for half- and full-cell modules under different partial shading conditions. The high tolerance of half-cell modules makes these particular modules resistant in the case of, for example, dust accumulating in the corners of the modules.

Two solar modules with 72 full and 144 half cells on Fraunhofer CSP's outdoor roof test lab were measured over the period 08/2013 to 04/2014 (see Fig. 9). While the module power difference under STC conditions was $4.6\%_{rel.}$, the average energy yield difference was only $3\%_{rel.}$.

To carry out a comparison of the energy yields with respect to the irradiation and module temperature, the measured energy yields were evenly distributed and averaged in intervals of $50W/m^2$ irradiation and 2°C module temperatures of the half-cell module. Fig. 10 shows that with increasing irradiation and module temperature, the difference between the energy yields increases. A relative yield difference of up to 6% between the half-cell and full-cell module was measured at high irradiation conditions. Under low-irradiation conditions, the energy yield difference can drop to less than 2% [15]. Higher irradiance leads to larger module currents and greater electrical losses; thus, the benefits for half-cell modules are greater

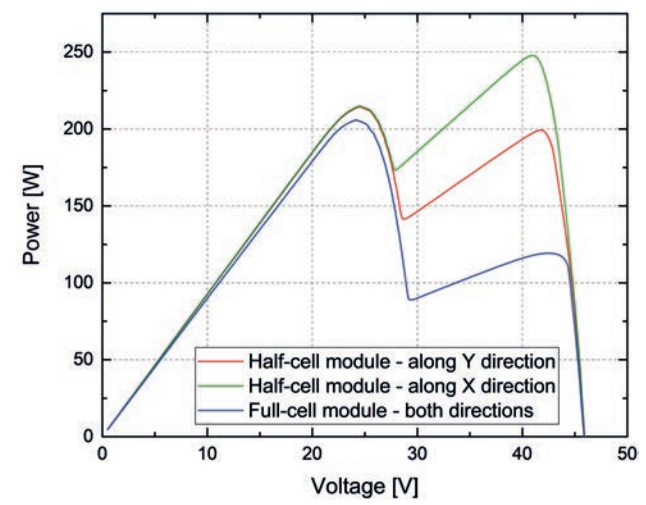

Figure 8. Power–voltage curves for comparable half-cell and full-cell modules, when one solar cell or two half cells are affected by 70% shading in two different directions. The half-cell module shaded along the *x* direction still has all its strings in operation [14].

at higher irradiance. Half-cell solar modules are consequently particularly well suited to applications in high-irradiation regions in sunbelt areas; for example, in Morocco an additional gain of up to 2.2% is expected, as compared to 1.5% in Germany [11].

"Half-cell solar modules offer many benefits and have the potential for setting a new standard technology."

Figure 9. A half-cell module (left) and a full-cell module (right), installed at Fraunhofer CSP's 'Outdoor PV Lab Halle' outdoor setup.

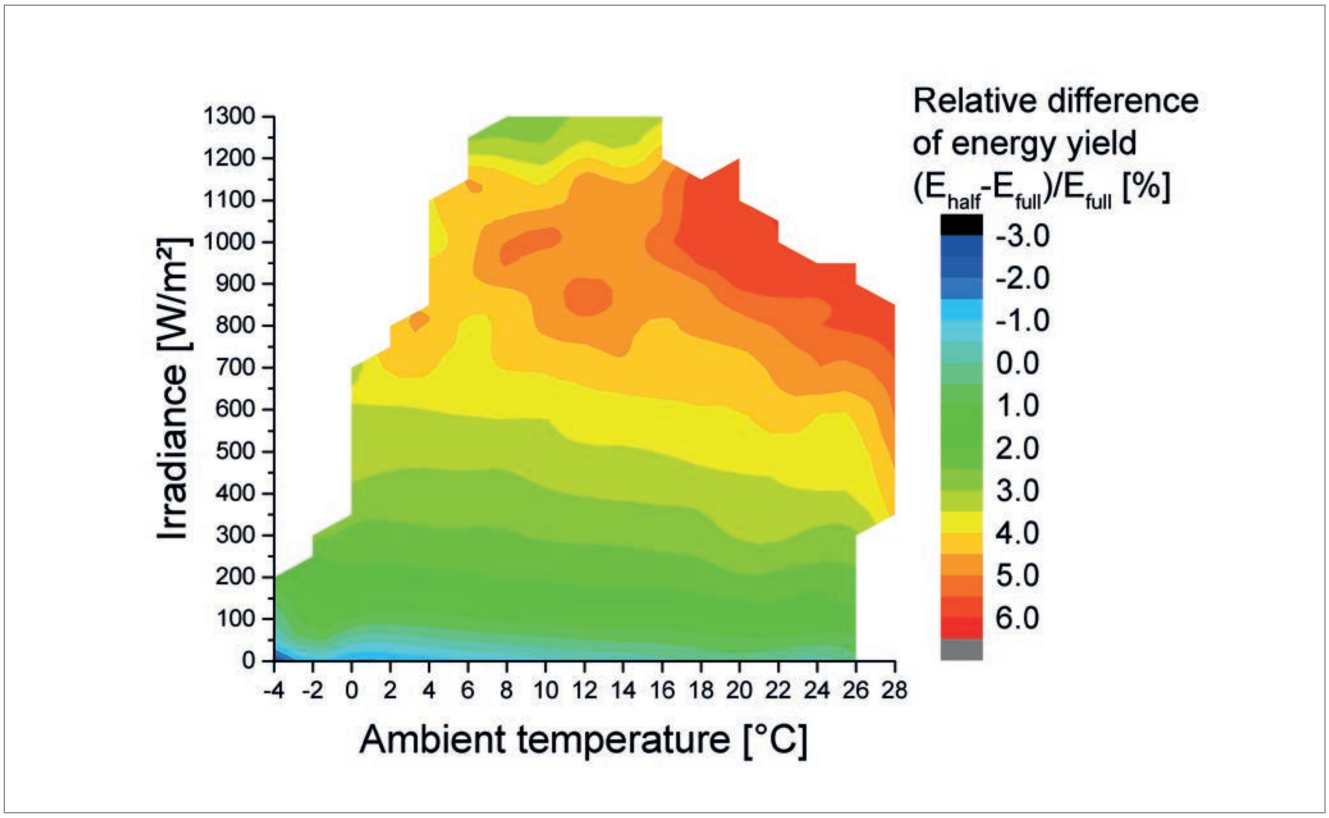

Figure 10. Relative yield gain of the half-cell module compared with the full-cell module ($(E_{half} - E_{full}) / E_{full}$). The measured yield values for each module were summarized according to irradiation and temperature, and then averaged (intervals: 50W/m^2 irradiance, 2°C module temperature).

Investment analysis

On the assumption that a solar module factory produces one module per minute for 24 hours and 365 days per year at 300W per module, the total output is 158MW per year. If the module power is increased by 5% for half-cell modules, an extra 7.9MW is generated each year. At $0.2 per Wp module sales price, an extra earning of more than $1.5m per year is feasible; this extra margin would have to pay for an additional cell cutting tool, double tabber–stringer capacity, modification of lay-up and bussing. A decentralized junction box must be sourced at a similar cost to a central one. Since particularly the cell cutting tool and the additional tabber–stringer capacity require additional floor space, it is much easier to plan new solar module production capacity in a half-cell design than to retrofit existing lines. For new solar module lines, the payback period should be less than one year, making half-cell solar module lines extremely attractive.

Summary

Half cells offer a simple route to achieving substantial power gains in solar modules. A power gain of up to 5% is possible with an optimized module layout without a change in size, and up to 8% with larger modules. Payback periods of below one year are expected for new solar module lines. Half-cell solar modules are particularly well suited to sunbelt regions, since the power gain is only translated to an energy yield gain and a levelized cost of electricity (LCOE) reduction when the irradiance is high. The solar cell cutting process must be sufficiently well controlled with regard to mechanical properties, in order to avoid cell cracking and performance losses in the field.

Once low-damage processes are under control, further developments in solar modules can include even smaller cells with multiple cuts in one direction, such as shingle cells and modules, or in two directions for more flexible module designs.

Half-cell solar modules offer many benefits and have the potential for setting a new standard technology for quite some time, at least until new module technologies are developed.

References

[1] ITRPV 2018, "International technology roadmap for photovoltaic (ITRPV): 2017 results", 9th edn (Mar.) [http://www.itrpv.net/Reports/Downloads/].

[2] Schneider, J. et al. 2014, "Solar module with half size solar cells", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, p. 185.

[3] Guo, S. et al. 2015, "Investigation of the short-circuit current increase for PV modules using halved silicon wafer solar cells", *Sol. Energy Mater. Sol. Cells*, Vol. 133, pp. 240–247.

[4] Schönfelder, S. et al. 2006, "Strength characterization of laser diced silicon for application in solar industry", *Proc. 21st EU PVSEC*, Dresden, Germany, pp. 588–592.

[5] Schneider, J., Schönfelder, S. & Kaufmann, K. 2016, "Method for splitting of plate-shaped objects made of brittle materials", European Patent Appl. No. EP2990172A1.
[6] Eiternick, S. et al. 2014, "Loss analysis for laser separated solar cells", *Energy Procedia,* Vol. 55, pp. 326–330.
[7] Eiternick, S. et al. 2015, "High quality half-cell processing using thermal laser separation", *Energy Procedia,* Vol. 77, pp. 340–345.
[8] Kaule, F. et al. 2018, "Mechanical damage of half-cell cutting technologies in solar cells and module laminates", *AIP Conf. Proc.,* Vol. 1999, No. 1, 020013.
[9] McIntosh, K.R., Swanson, R.M. & Cotter, J.E. 2006, "A simple ray tracer to compute the optical concentration of photovoltaic modules", *Prog. Photovolt: Res. Appl.,* Vol. 14, pp. 167–177.
[10] Haedrich, I. et al. 2014, "Unified methodology for determining CTM ratios: Systematic prediction of module power", *Sol. Energy Mater. Sol. Cells,* Vol. 131, pp. 14–23.
[11] Hanifi, H. et al. 2016, "Optimized tab width in half-cell modules", *Energy Procedia,* Vol. 92, pp. 52–59.
[12] Sander, M. et al. 2013, "Systematic investigation of cracks in encapsulated solar cells after mechanical loading", *Sol. Energy Mater. Sol. Cells*, Vol. 111, pp. 82–89.
[13] Lu, F. et al. 2013, "Improved PV module performance under partial shading conditions", *Energy Procedia,* Vol. 33, pp. 248–255.
[14] Hanifi, H., Schneider, J. & Bagdahn, J. 2015, "Reduced shading effect on half-cell modules – measurement and simulation", *Proc. 31st EU PVSEC,* Hamburg, Germany, pp. 2529–2533.
[15] Malik, S. et al. 2014, "Outdoor data evaluation of half-/full-cell modules with regard to measurement uncertainties and the application of statistical methods", *Proc. 29th EU PVSEC,* Amsterdam, The Netherlands, p. 3269–3273.

About the Authors

Jens Schneider received his Ph.D. from Technische Universität Berlin and Hahn-Meitner-Institut Berlin. He worked for CSG Solar AG from 2005 to 2011 in process development, after which he joined Fraunhofer CSP as the module technology group manager. In 2014 he became a professor at Leipzig University of Applied Science, teaching photovoltaics and sector coupling. He transferred to the Fraunhofer Center for the Economics of Materials CEM in 2019, where he is involved in directing efforts in energy system analysis.

Hamed Hanifi received his master's in electrical power engineering from Brandenburg University of Technology (BTU) in Cottbus, Germany, in 2015. Since then he has been pursuing his Ph.D. at Martin Luther University Halle-Wittenberg, with a focus on PV module optimization for desert applications. Since 2015 he has also been working at Fraunhofer CSP, as well as at Anhalt University of Applied Sciences in Koethen, Germany, as a scientific researcher, where he specializes in optimization of cell-to-module power ratios of standard modules, and in optimization of PV modules for desert applications.

David Dassler received his M.Sc. in applied mathematics from Leipzig University of Applied Sciences. Since 2012 he has been working at Fraunhofer CSP in the reliability of solar modules and systems group, specialising in yield analysis. In 2015 he began his Ph.D., with a thesis topic of yield modelling in desert climates.

Matthias Pander studied mechanical engineering at the Leipzig University of Applied Sciences. He graduated in 2010 with a master's, for which his thesis dealt with the simulation of thermomechanical stresses in embedded solar cells. He works on PV module simulation and reliability testing in the reliability of solar modules and systems group at Fraunhofer CSP.

Felix Kaule studied mechanical engineering at HTWK Leipzig. Since 2012 he has been working as a research scientist in the mechanics of wafers and cells team at Fraunhofer CSP. His research focuses on strength analysis of silicon wafers and cells by means of the finite-element method and statistical evaluations.

Dr. Marko Turek studied physics at Dresden University, and received his Ph.D. in the field of condensed matter theory from the University of Regensburg. At Fraunhofer CSP he leads the team involved with electrical characterization of solar cells and modules. His research focuses on loss analysis of solar cells, advanced characterization methods and development of new test methods and devices.

Enquiries

Jens Schneider
Fraunhofer Center for Silicon Photovoltaics CSP
Otto-Eissfeldt Str. 12
06120 Halle (Saale), Germany