Rijksdienst voor Ondernemend Nederland

Openbaar eindrapport BING ECN-E--18-021

Gegevens project

- Projectnummer: TKI Toeslag
- Projecttitel: BIfacial eNergy Gain
- Penvoerder en medeaanvragers:
  - ECN – Solar Energy
  - Tempress Systems BV
  - Veco BV
  - Yingli Energy (China) Co., Ltd.
- Projectperiode: September 2015 – December 2017
- Publicatiedatum openbaar rapport:

Samenvatting van uitgangspunten, doelstelling en samenwerkende partijen

Even though solar electricity products have seen a significant growth in the past years, the introduction of novel technologies is needed for further cost and price reduction, and to maintain the current learning curve in order to keep one step ahead of the competition. Hence, the future competitiveness of cell and module concepts relies ever more on innovation towards high efficiency, cost effectiveness in €/Wp and reliability. This provides challenges but also huge opportunities for (Dutch) manufacturers of the enabling equipment and high-volume-manufacturing tools. Bifacial solar cells in combination with double glass module technology is one of the ways to further decrease the levelised cost of energy in €/kWh.

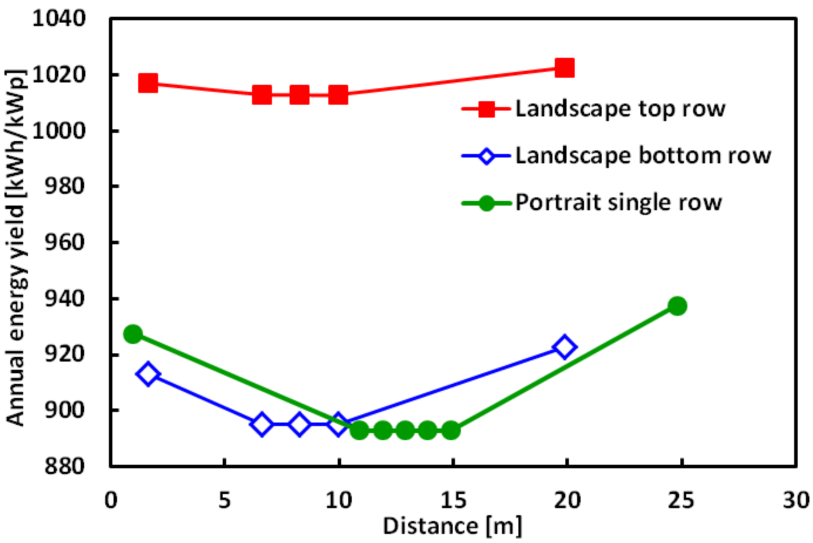
The project BING aims to validate, understand and improve the energy yield of bifacial PV systems and double glass modules based on the ECN's bifacial n-Pasha solar cell. A higher energy yield leads to lower electricity production costs and improved environmental profile.

ECN – Solar Energy
Tempress Systems BV
Veco BV
Yingli Energy (China) Co., Ltd.

Beschrijving van de behaalde resultaten, de knelpunten en het perspectief voor toepassing

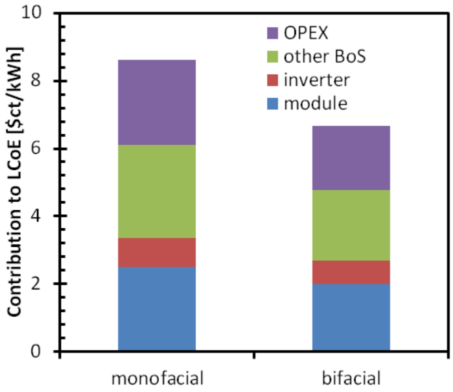
Bifacial energy yield model

The bifacial energy yield model has been validated on small systems and some minor errors were corrected. Further validation on larger systems is included in granted TKI-projects.



Bifacial system optimisation has been applied to the question of landscape or portrait orientation of the bifacial modules. In the model we compare a system of about 125 modules. In portrait orientation 5 rows of 25 modules were evaluated; in landscape orientation each, of in total 5, rows consisted of 12 modules wide and 2 module high. Annual yield data for some of the modules in the middle row are shown in the graph below as a function of their position. Clearly, portrait orientation yields the lowest energy per year. Also the position has a strong effect on the variation in energy per year. Both effects are due to the shading of neighbouring rows. As the shade approaches the module from the bottom edge, all cells on the bottom edge are shaded simultaneously. In portrait orientation, this means that all three cell-strings will have a reduced maximum current due to the shade, whereas in landscape orientation, only cells in the bottom cell-string are effected initially. Modules located at the edges of the rows are less effected as the shade is oriented mostly towards the North. Modules at the northern edge do not benefit from less shade than their neighbours, but benefit from a less restricted view factor towards the sky.

Levelised cost of electricity



The levelised cost of electricity (LCoE) is compared for two similar systems, one consisting of monofacial, multicrystalline modules with polymer back sheet, the other containing n-PERT bifacial glass-glass modules. The difference in module type effect the annual energy yield, the module efficiency, the lifetime and the costs of the modules. Note the module efficiency as such has no direct influence on the LCoE, but area-related costs are reduced as fewer modules are needed for the same peak power. A simple model has been applied, ignoring aspects like taxes, and subsidies.

Applying typical values for a system based in the Netherlands, we find that the LCoE for a system with bifacial modules is 23% lower than that for a system with monofacial modules. Where the latter yields 8.6 $ct/kWh, replacing the modules with bifacial modules lowers the LCoE to 6.7 $ct/kWh. The graph shows the contribution of the cost components to the overall LCoE. All parts are lower for the bifacial system, with OPEX and other BoS at -24% and module at -19%. The larger reduction in OPEX and other BoS is due to the higher module efficiency that decrease the area-related costs. The module costs per Wp are actually higher due to the premium price for high-end products.

Most of the reduction is due to the increased annual energy yield in the bifacial system, but also the increase in (operational) lifetime has a significant effect. The lower land use is more or less annulled by the premium price, compared to monofacial p-type mc-Si.

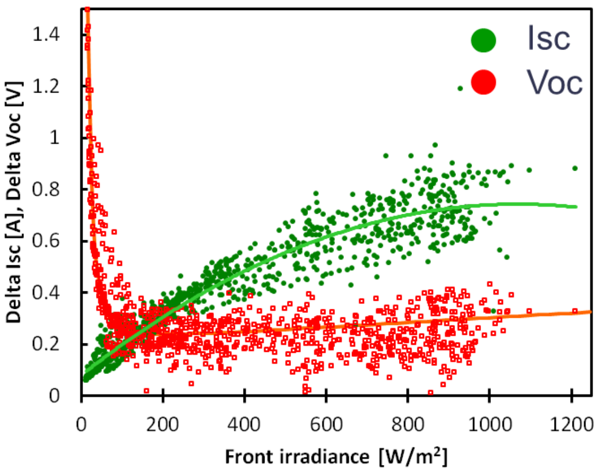
Observed bifacial energy gain

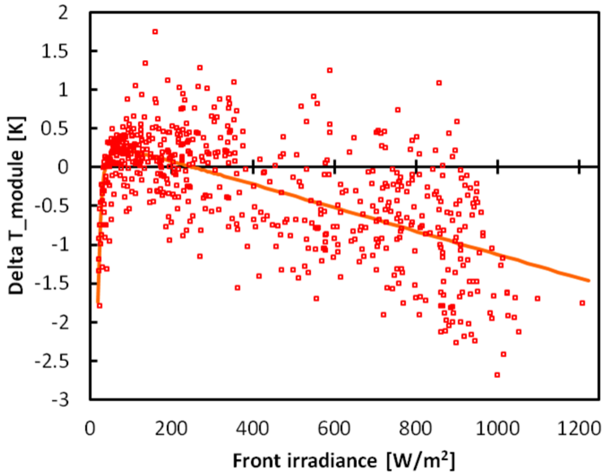
One large system was analysed in the BING project. The Datong project was connected to the grid in June 2016. The, at commissioning, largest bifacial PV plant in Datong, China shows an increase in energy gain of at least 10% during the first year of operation.

We also analysed the bifacial gain for (commercial) modules on ECN’s roof top. Bifacial modules on ECN’s rooftop yield 5% gain relative to identical monofacial modules placed above concrete for irradiance above 0.2 sun. At low irradiance, say below 0.2 sun, the gain is, on average, 10%. To improve the bifacial gain and understand the effect of albedo, the concrete was painted white with conventional, cheap concrete paint from a DIY store. The white underground increases the irradiance on the rear significantly, resulting in an over 10% gain at high irradiance conditions. At lower irradiance conditions below 0.5 sun, the bifacial gain already increases. At even lower front side irradiance, the gain is 15% at 0.2 sun to >30% at lowest irradiance.

Observed bifacial module temperature

We monitored two bifacial and two monofacial modules from the same company with the same quality/type of solar cells installed at ECN’s rooftop at 30° tilt and south-facing. We calculated the difference “bifacial – monofacial” in Isc, Voc and module temperature. The differences are plotted as a function of the observed in-plane front irradiance. Clearly, the bifacial Isc is (much) higher than the monofacial Isc. The gain is over 15% at low irradiance, but saturates somewhat at 7% around 1 sun front irradiance. The much larger Isc, due to the relatively large rear irradiance, at lowest irradiance causes a large increase in Voc ($\Delta V > 1$ V), as the Voc shows a logarithmic dependence on the generated photocurrent (= total irradiance). The difference in Voc drops dramatically to $\Delta V \approx 0.2$ V around 200 W/m^2 irradiance as the effect of the irradiance on Voc becomes less pronounced. One would expect that the drop would continue towards 0 V at high irradiance, unless the influence of the temperature on the Voc would become significant. Indeed, a small increase in ΔV to about 0.3 V with increasing irradiance is observed, suggesting that despite the diminishing effect of the increasing irradiance on the voltage difference the bifacial Voc increases faster. This can only be explained if the difference between the bifacial and monofacial module temperature changes with the bifacial module becoming (relatively) cooler. The graph on the right shows the ΔT, clearly a decreasing trend is observed indicating that the bifacial modules become cooler, with $\Delta T < -1$°C near 1000 W/m^2 irradiance. We also observe that at very low irradiance, values typical for the first and last measurements of the day, the bifacial modules are also significantly cooler. This is consistent with a large(r) radiative cooling effect in glass-glass modules.





Increased understanding of bifacial gain

During the project, the various lab and outdoor experiments lead to an increase in the understanding of how and why bifacial PV systems would lead to higher energy yield. In no particular order, these are summarised here. Details can be found in the public presentations and articles given at the end of the report.

1. Although a high *albedo* leads to some additional heating of bifacial modules, the loss in power due to higher operating temperatures is more than offset by the increase in Isc due to the increase in ground-reflected light.
2. Next to the obvious increase in rear efficiency, a high bifaciality factor is also favourable in preventing parasitic heating by rear irradiance.
3. Although solar cells and modules are characterised at 1000 W/m^2, most of the times, the PV panels are irradiated, front plus rear, with much less than that. The bifacial energy yield can be optimised by optimising the metallisation grid.
4. The preferred landscape orientation is maintained for bifacial modules, but the losses due to shading are somewhat reduced, from nearly 8% to just over 7%, compared to monofacial modules.
5. The inhomogeneity of the rear irradiance over all 10 x 6 solar cells due to system design, different view factors to sky and ground and junction boxes, cables, etc. could be pretty large, but in most cases this is compensated by a much larger front irradiance. Power loss is minimal, and dangerous, hot spot, situations are almost excluded. These issues can be further reduced by keeping a minimal distance between the rear of the panels and other object, by making sure those objects are partially reflecting and by placing them between rows of cells instead of in the centre of a line of cells.
6. For east-west vertical systems, we have looked at the effect of row spacing on the power output. Obviously, with decreasing spacing the power output decreases. However, it appears as if there are two regimes. At large spacing, reducing the row-row distance “only” reduces the view factor; the modules “see” less of the sky; shading is insignificant. Reducing the distance even more, the neighbouring rows will start to shade each other. At even smaller spacing, reducing the row-row distance increases the energy loss due to shading more or less linearly.
7. We have identified two design parameters that effect the actual temperature of bifacial modules in the field. First, obviously, higher bifaciality reduces the cell temperature as less light is (parasitically) observed in doped or metallised areas. Secondly, glass-glass modules and laminates have the same temperature or are even cooler than (white) back sheet laminates, despite absorbing significantly more energy from the rear. Possibly, the energy transfer from glass to air is more efficient and/or the radiative losses through glass are more pronounced than through back sheet.

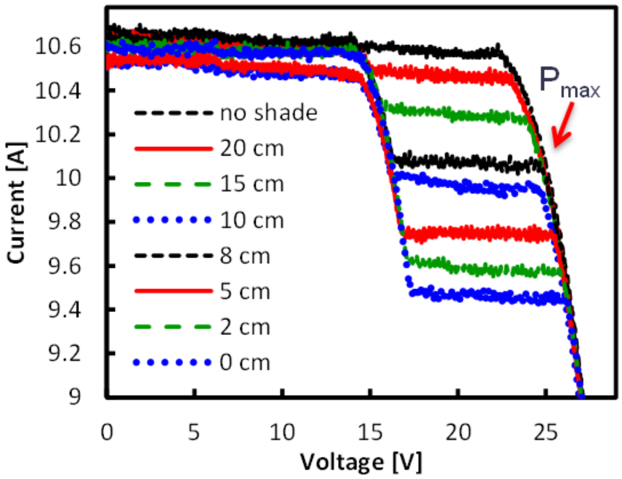
Mismatch losses due to inhomogeneous rear irradiance

We measured the rear irradiance on each solar cell for a full-size module on an outdoor rack on ECN’s rooftop, see photograph. The distribution of rear irradiances is shown in the right figure. Clearly, the lowest irradiance is about half of the highest irradiance. Note, however, that the irradiance on the front is about 10x larger than the highest irradiance.

	A	B	C	D	E	F
1	65	64	63	63	63	62
2	75	74	73	74	75	77
3	72	70	69	69	68	72
4	66	65	65	66	68	70
5	53	50	47	49	52	57
6	54	51	49	51	52	56
7	53	54	55	56	58	61
8	62	59	56	58	59	63
9	66	61	56	59	61	66
10	72	67	62	65	69	75
11	79	78	76	77	78	79
12	76	73	70	73	77	83

To investigate the effect of this rear irradiance distribution, a LT-spice model was made for 72 solar cells in series. Three different distribution of irradiances were evaluated by varying the generated (photo)current keeping all other 1-diode parameters the same and calculating the IV curve with bypass diodes. First all cells were regarded with the same total photocurrent, corresponding to the highest value. Then, all cells had photocurrents that corresponds to the above given values. This resulted in a 5 W drop in Pmax. Finally, we looked at the case that all cells had uniform photocurrent that had the same average irradiance on module level as the inhomogeneous case. In the final case, the Pmax did not differ significantly from the inhomogeneous case. In conclusion, inhomogeneous irradiance does decrease the power output, but does not lead to mismatch losses or worse.

We also investigated this effect in the lab. We simulated rear irradiance by placing white scattering surface about one metre behind a bifacial module and illuminated that module with a steady state solar simulator. As a result, the module Isc increased by about 20% (see black curve). Then we placed a 15x20 cm^2 black piece of cardboard 20 cm behind one cell of that module and measured the IV whilst decreasing the distance. Clearly the effect of the "rear" shade is visible as the current in one of the strings is reduced from 10.6 to 9.5 A. Note that the Impp of the module, under "bifacial" illumination is just over 10 A. As a consequence, Pmax is not effected when the shading object is 8 cm or more behind the module. At closer distances the loss in power increases rapidly.

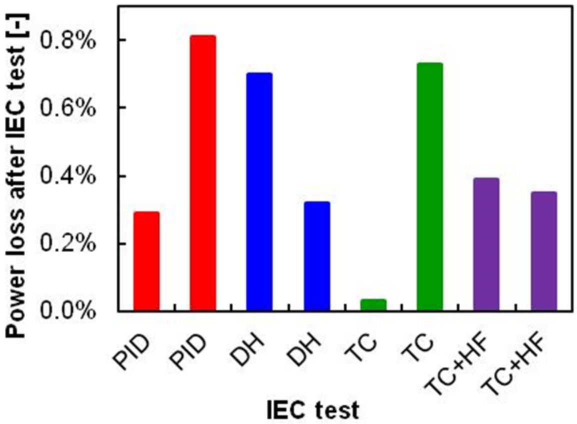


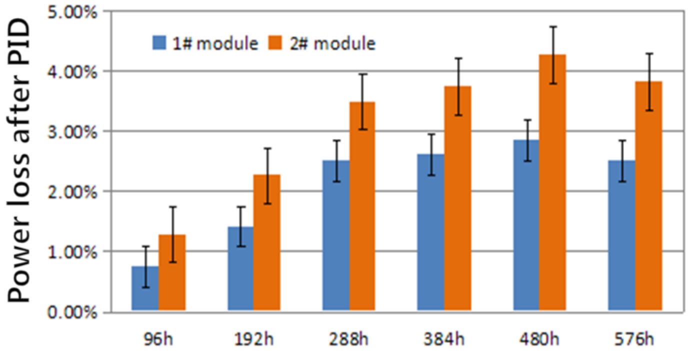
Reliability

As the risks of hot spots due to inhomogeneous irradiance is not increased relative to monofacial module this work was cancelled. IEC testing was performed on commercial bifacial Panda modules. Extended PID testing was performed to show the limited effect of PID for n-PERT double glass modules.

Yingli put bifacial Panda modules through the IEC testing sequence. Each test was performed on two modules. Power loss was determined after each of the test, including a combined thermal cycle & humidity freeze test. All power losses were limited to <1%.

As ECN published that PID could affect n-PERT PV modules too, it was decided to test full-size modules under extended PID exposure at 60°C and 85% RH. The IEC-test condition is at the same conditions for 96h. 5% power loss is allowed. Yingli's bifacial Panda modules show 1% after 96 h and 3-4% after almost 500 hours

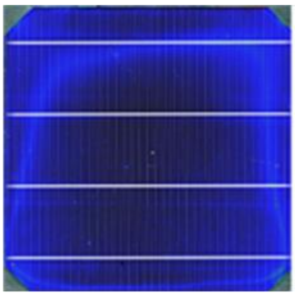


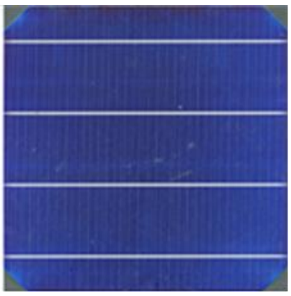


In conclusion, hot spot conditions are not likely to occur due to inhomogeneous rear irradiance. Yingli's double glass Panda modules are IEC qualified and pass all test with <1% power loss. Yingli's double glass Panda modules show less than 5% PID degradation even after prolonged exposure. The PID power loss also stabilises in contrast to shunt-PID in p-type modules where the power loss continues to >50%.

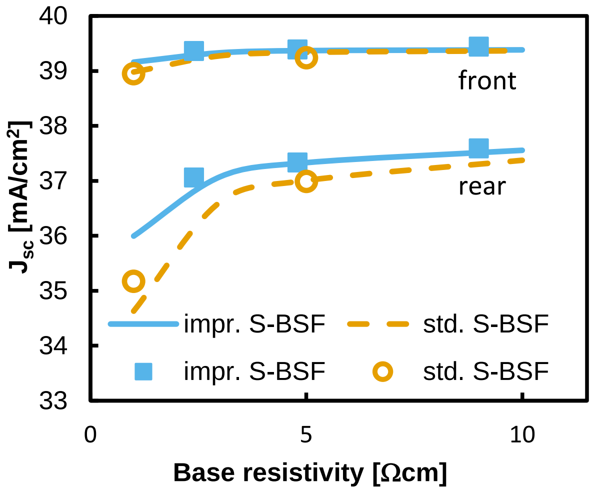
Rear surface morphology

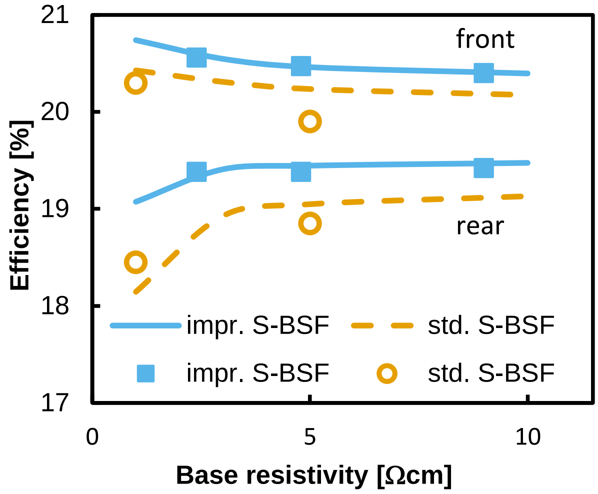
The standard n-Pasha process is optimised only for front side performance. Below photographs of the rear side of two n-Pasha solar cells are shown. The left hand side shows the rear of an n-Pasha solar cell with non-optimised BSF processing. This cell shows clearly an inhomogeneous rear side. Optimising the BSF process results in the right hand image where no inhomogeneities are visible.


Non-optimised BSF


Optimised BSF

We also measured and simulated the IV-curves for these solar cells with several base resistivities ρ_base of the wafers. The graphs below show the Jsc (left) and conversion efficiency (right), symbols represent experimental data, whereas the lines represent simulated data. First, we observe a large decrease in Jsc for the rear at low ρ_base, this results in low bifaciality factors at low ρ_base. Improving the BSF processing yields a small increase in Jsc for the rear for all wafers, but the largest effect at low ρ_base. The front side Jsc is not improved.

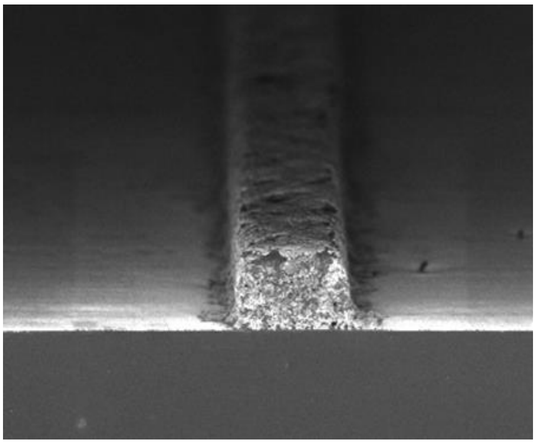


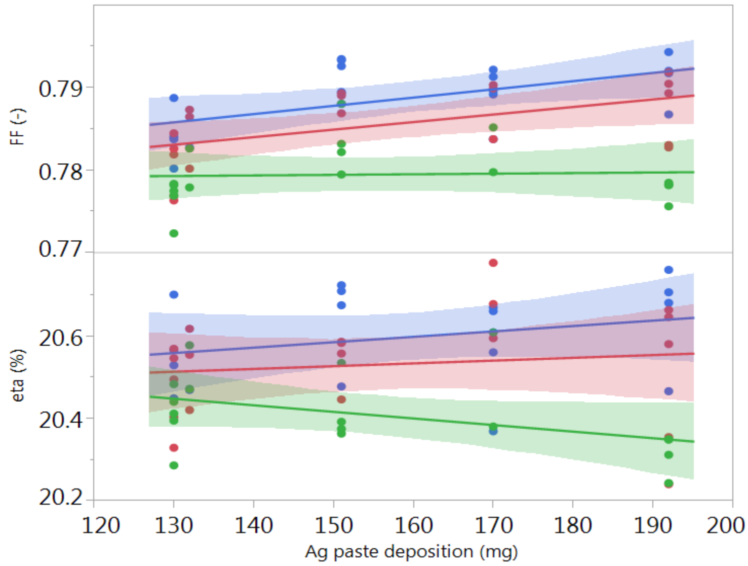


Looking at the efficiency, we see that both the front and rear efficiencies improve with the optimised BSF, but the effect is larger for the rear and most significant at low ρ_base.

Rear side cell metallisation

An electron microscope image of a stencil printed finger is shown below. The clear rectangular cross-section is well visible. Note also the homogeneity of the thickness in the parallel direction of the finger and the very limited spread of metallisation paste along the solar cell surface.



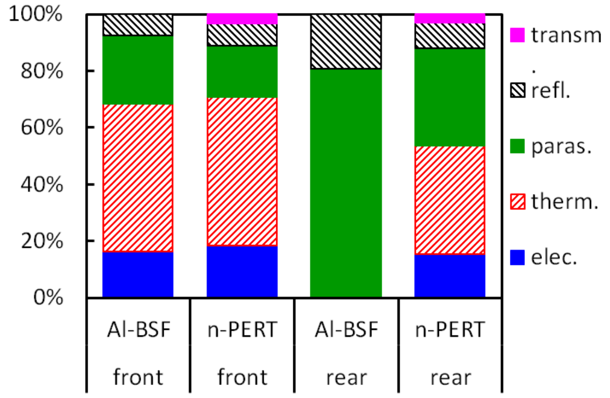


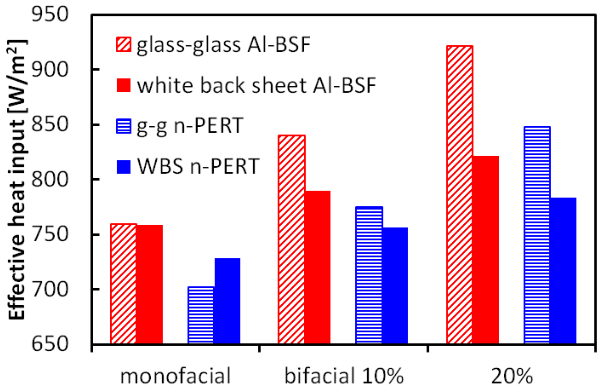
To limit the cost of the bifacial solar cell, the effect of printing less Ag on the rear side was investigated for solar cells processed on wafers with three different base resistivities. The Ag paste reduction is achieved both by reducing the finger width as well as the number of fingers. The results of IV measurements for *front* illumination are shown. The FF for the low and middle base resistivity show a tendency to decrease with decreasing Ag paste deposition. For the high base resistivity solar cells the FF is not effected by the reduction in Ag paste consumption. However, improvements in Voc and Isc annul all effects and no significant change in front side efficiency is observed for any set of solar cells with decreasing Ag paste deposition. The 30% lower Ag consumption brings the rear Ag load in the same range as the front side. Note that as we have not observed a decrease in efficiency, an even lower Ag paste coverage might be possible without compromising the monofacial or bifacial cell efficiency.

Understanding solar cell heating under illumination

The IV-curves, spectral response and reflection/transmission have been measured for a whole range of monofacial and bifacial solar cells and laminates with white back sheet or glass rear panel. All samples, including the monofacial ones, have been measured with illumination on the front and on the rear. From these measurements, we have spectrally resolved where the energy of the full AM1.5 spectra ends up. First there is the optical losses due to *reflection* and also *transmission*. The latter mainly near infra-red light and only for bifacial solar cells and glass-glass laminates. All other light is absorbed. A significant part is used to generate the photocurrent, but a large part of that energy is lost due to thermalisation, i.e. the excess energy between the absorbed photon (typically between 3 and 1.1 eV) and the Si band gap (1.1 eV). Another part is absorbed in the metallisation, Al BSF, module materials or as free carrier absorption in the doped regions. This we call parasitic heating. Finally, there are losses in the solar cell due to recombination, entropy and resistive losses.

In the bar diagram we show this distribution for an Al-BSF solar cell and a bifacial n-PERT solar cell, both for front and rear illumination. All electricity-generating measurements show 70-75% heating due to parasitic absorption and thermalisation. As the parasitic absorption for the n-PERT rear side is mostly in the high-energy “blue” region, the thermalisation losses are relatively smaller compared to the generated electric energy, but the total heat input is still larger than for front illumination . In contrast, almost 80% of all energy that falls on the rear side of an Al-BSF solar cell is converted into heat without any electrical energy. Reducing the (parasitic) absorption in layers on the rear is an important improvement, not only for the (rear side) efficiency but also to reduce the parasitic absorption and associated heating of the solar cell under illumination.

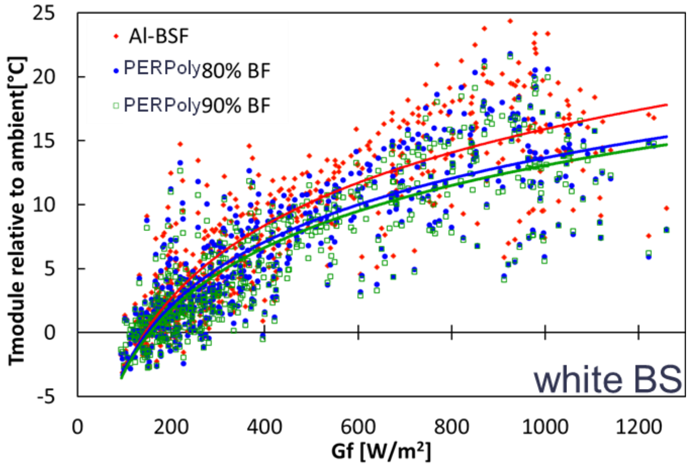




The right hand graph shows the effective heat input for these solar cells when incorporated in glass-glass (dashed) and white back sheet (filled bars) for three situations. Monofacial, that is 1000 W/m^2, “bifacial 10%”, that is 1000 W/m^2 front and 100 W/m^2 rear and , “bifacial 20%”, that is 1000 W/m^2 front and 200 W/m^2 rear. The additional (rear side) irradiance increases the effective heat input significantly more for the glass-glass laminates, in particular with Al-BSF solar cells, compared to the white back sheet modules where most of the rear light is reflected. These results suggest that bifacial glass-glass laminates, especially under high rear irradiance conditions, will heat up more both compared to bifacial solar cells in monofacial modules and compared to “standard” white back sheet modules with Al-BSF solar cells.

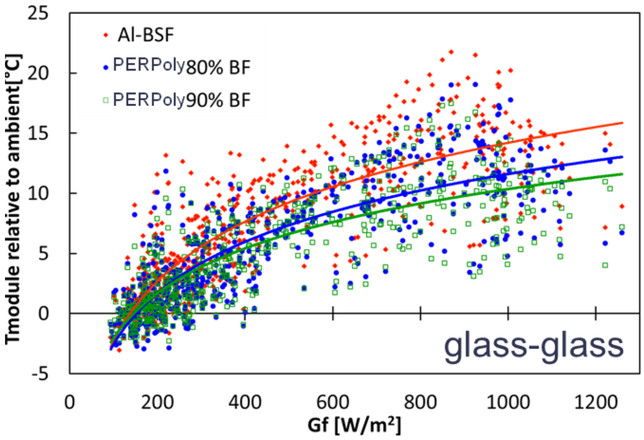
Effect on reducing FCA on observed solar cell temperatures in laminates under outdoor conditions

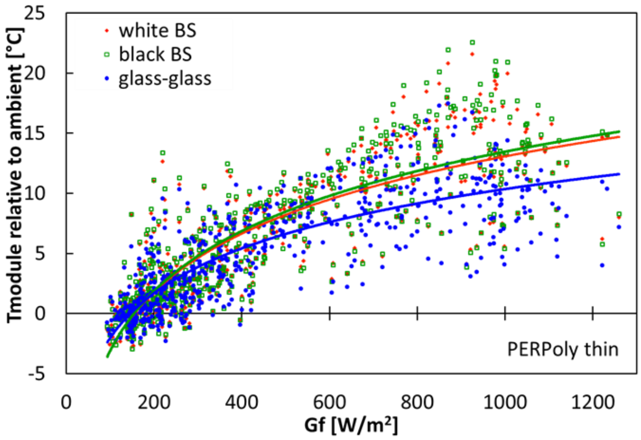
A set of single-cell laminates with different cell concepts and different rear side materials has been monitored on ECN’s roof top. For each single cell laminate, Voc and Isc are determined every 10 minutes. From the observed Isc, a measure for the effective irradiance, and observed Voc, the actual cell temperature can be deduced. The right hand graph shows the difference between the calculated and ambient temperature as function of the measured front irradiance. Spread in the data is, amongst other effects, caused by varying wind speed and varying rear irradiance. Three different cell concepts are compared in monofacial white back sheet laminates. Clearly, the laminates with Al-BSF solar cells shows a somewhat higher module temperature, compared to the laminates with the two bifacial cell concepts. At 1000 W/m^2, Al-BSF is +16°C above ambient and the bifacial ones +13°C. The difference between Al-BSF and the 90% bifaciality factor PERPoly solar cell is on average 3°C. Much harder to distinguish, the laminate with highest bifaciality (green, open squares) have a somewhat lower temperature compared to the 80% bifaciality (blue circles). At 1000 W/m^2, calculated differences fall between -0.3°C and +1.0°C.



We also compared the same cell concepts in bifacial, glass-glass laminates. Again the laminate with the Al-BSF solar cell show the highest increase, +14°C, with increasing front irradiance, and the laminate with the 90% bifaciality factor solar cell the lowest increase, +10°C, above ambient.

The final graph shows the module temperature for three different rear materials using the PERPoly solar cells with highest bifaciality. Note that both white and black back sheet (BS) are white on the outside, that is rear side. Only the colour on the inside, facing the solar cells and visible from the front is different for aesthetic reasons. Both monofacial laminates with either back sheet show the same temperature increase above ambient. At 1000 W/m^2 this is on average +13°C. Clearly different, the bifacial laminates exhibits only +10°C, above ambient.





From our indoor measurements and calculations, we showed that glass-glass laminates have a higher effective heating compared to white back sheet laminates, with Al-BSF in glass-glass having the highest effective heat input under bifacial irradiance. However, the outdoor results show that the Al-BSF solar cells have a 2°C lower temperature in glass-glass laminates then in white back sheet laminates, for bifacial solar cells this difference is even larger. The lower actual temperature for glass-glass laminates can be related to differences in radiative properties between a glass and a polymer rear panel or to differences in heat transfer from rear panel to air.
These results will be presented in full at the 2018 SiliconPV conference in an oral presentation as one of the top20 abstracts.

Beschrijving van de bijdrage van het project aan de doelstellingen van de regeling (duurzame energiehuishouding, versterking van de kennispositie)

One of the aims of the TKI solar energy, at the time the proposal was written, was to achieve 3% PV in the Dutch electricity market by 2020, corresponding to 4 GWp installed capacity at an average annual yield of 900 kWh/kWp.
In BING, we have shown that bifacial gains of 10% are achieved without any additional effort to increase the albedo or adept the mounting of the module. The annual yield for bifacial PV is thus expected to be at least 1000 kWh/kWp. Increasing the albedo of the underground increases the rear irradiance from 10% to 30% of the front irradiance.

Another aim is to get the production cost of PV electricity in the range of 8 to 10 cents per kWh. Admittedly, the decrease in average sales price of modules in the last few years made a significant impact. We have shown that the LCoE for a bifacial system in the Netherlands at 20% bifacial gain is 1.9 $ct/kWh lower compared to a system with cheaper monofacial modules.

The work has been presented at the large European and Asian conferences, but also at specialist meetings like the SiliconPV conference and bifiPV workshop. ECN's bifacial yield model is one of the most advanced models that have been presented in public. Both the optical model and the electrical model, taking into account inhomogeneous irradiance and shading-induced bypass diode switching, are state of the art, if not unique.
Also the experimental determination of the inhomogeneity of the irradiance at the rear due to near-field objects and the full analysis on the temperature of monofacial/bifacial solar cells in various module configurations triggered positive response from other research institutes and companies alike. These subjects and the results and presentation were regarded as timely, "always suspected this, but never saw it confirmed" and of high quality.

Spin off binnen en buiten de sector

The bifacial energy model for PV plants is applied in the TKI-project Subsol to optimise floating PV plants. ECN has received requests from commercial partners to apply the model to their PV projects.

The increased understanding of the heat input and the actual operating temperature in real life have created positive feedback from our colleagues, both in research and in industry. ECN will publish these results in a peer-reviewed paper and look for follow-up projects with Dutch industrial partners.

Overzicht van openbare publicaties over het project en waar deze te vinden of te verkrijgen zijn

The research done in BING has been presented at several conferences and workshops in Europe and Asia. Most articles and the presentations at the bifiPV workshops are available for download.

B.B. Van Aken et al., "*White Bifacial Modules – Improved STC Performance Combined with Bifacial Energy Yield*", Proc. 32nd EU PVSEC (2016) 42-47.
Available at http://www.eupvsec-proceedings.com/proceedings?paper=38754 .

B.B. Van Aken, "*Review on module and system simulations*", bifiPV workshop, Miyazaki (2016).
Available at http://bifipv-workshop.com/index.php?id=myazaki-program.

B.B. Van Aken, "*White bifacial modules - improved STC performance and bifacial energy yield*", bifiPV workshop, Miyazaki, Japan (2016).
Available at http://bifipv-workshop.com/index.php?id=myazaki-program.

A. Carr et al., "*An energy yield model for bifacial photovoltaic systems*", 26th PVSEC, Singapore (2016).

B.B. Van Aken et al., "*Bifacial aspects of industrial n-Pasha solar cells*", Jap.J.Appl.Phys. **56** (2016) 08MB03.
Available at http://iopscience.iop.org/article/10.7567/JJAP.56.08MB03.

K.M. de Groot and B.B. Van Aken, "*Near-field partial shading on rear side of bifacial modules*", En.Proc. **124** (2017) 532-539.
Available at https://www.sciencedirect.com/science/article/pii/S1876610217341851.

G. Janssen et al., "*Aspects of bifacial cell efficiency*", En.Proc. **124** (2017) 76-83.
Available at https://www.sciencedirect.com/science/article/pii/S1876610217343059.

G. Janssen et al., "*Impact of Inhomogeneous Irradiance at the Rear of Bifacial Panels on Modelled Energy Yield*", Proc. 33rd EU PVSEC (2017) 1618-1623.
Available at http://www.eupvsec-proceedings.com/proceedings?paper=41607.

B.B. Van Aken, "*Bifacial PV: hot or cool? Or both!*", bifiPV workshop, Konstanz (2017).
Available at http://bifipv-workshop.com/index.php?id=konstanz-2017-program.

B.B. Van Aken, "*Bifacial PV: hot or cool?*", China Silicon PV conference (2017).

Accepted for an oral presentation and peer-reviewed publication in Solar Energy Materials and Solar Cells:
B.B. Van Aken et al., "*Temperature Effects of Bifacial Modules: Hot or Cool?*", SiliconPV (2018).

Meer exemplaren van dit rapport

Meer exemplaren van dit rapport kunnen digitaal worden verkregen via het hieronder genoemde contact.

Contact voor meer informatie

Meer informatie over dit project kan verkregen worden via:

- Dr.Ir B.B. Van Aken – vanaken@ecn.nl

Subsidie

Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, door de TKI Urban Energy gefinancierd met middelen uit de TKI Toeslag Regeling.