Detailed power loss/gain characterization of PV modules with multi-busbar, half-cut cells and light-trapping ribbon

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ABSTRACT

Compared with three-busbar (3-BB) full-cell designs, the use of multi-busbar and half-cut cell technologies can significantly reduce resistive losses and thus allow higher cell and module efficiencies. At the same time, there is a net reduction in silver paste consumption for the electrodes of the solar cells. In addition to these approaches, light-trapping ribbon (LTR) has also shown potential for improving PV module performance. This paper presents a detailed simulation- and experiment-based study of the power gain arising from the implementation of multi-busbar, half-cut and LTR approaches. Both cell and module performance were modelled using a 2D finite-element grid modelling software package (Griddler) developed by SERIS. Several single-cell and large-size modules were fabricated, and the performances of various module designs were compared. On the basis of the results from the experiments and simulations, the optimum design (number of busbars, busbar width, number of fingers, etc.) of the cell/module was determined. The results show that, compared with a widely used 3-BB full-size cell module, an optimized multi-busbar halved-cell module with LTR can enhance the module performance by more than 5%. Finally, an economic analysis considering the change in the design is presented.

Introduction

To guarantee the long-term competitiveness of the PV industry, the cost of PV power generation ($/kWh) must be continuously reduced. Such reduction can be achieved in two ways: 1) by improving PV module performance (efficiency, annual energy yield, reliability); 2) by reducing manufacturing costs ($/Wp).

To improve the module efficiency/power, various advanced technologies can be incorporated, such as multi-busbar [1,2], halved-cell [3,4] and light-trapping ribbon [5,6]. These technologies have yielded promising results in terms of improving module performance. Multi-busbar technology has a twofold effect on module performance and cost: 1) higher cell efficiency as a result of the reduction in the effective finger length and lower silver consumption (narrower fingers); 2) greater module power as a result of the reduction in the effective series resistance of the interconnecting ribbons [7,8]. In addition, halved-cell modules also show promising potential for improving module performance with minimal cost increase. The increase in performance of halved-cell modules is the result of improved fill factor (*FF*) because of the reduced resistive power loss in the ribbons, and improved current because of the 'static concentration' effect of light scattered from the backsheet [4,9].

This paper investigates the electrical and optical effects on module performance of using multi-busbar, halved-cell and light-trapping ribbon approaches. Detailed simulation and experimental studies have been performed to quantify the gain in module power using the above-mentioned approaches compared with the widely used three-busbar (3-BB) full-cell PV module design.

> "A multi-busbar approach is an effective way to improve module performance."

Theoretical background

Multi-busbar module

It is well known that solar cell metallization significantly affects the optical and electrical performance of the cell and module. Optical performance is influenced mainly by optical shading due to metal coverage, which directly impacts the short-circuit current (I_{sc}) in the solar cell and module. At the same time, the cell metallization affects the electrical performance because of the series resistance introduced by the metal finger grid, metal-semiconductor contact resistance and emitter resistance. In the case of a PV module, the electrical performance is mainly influenced by the effective ribbon series resistance [3]. To enhance the cell/module power, the front metallization should therefore be optimized for minimum shading and resistive losses. A multi-busbar approach is an effective way to improve module performance, since it can offer the following advantages:

1. The metal grid finger length is shortened, which results in a reduction in effective finger resistance; thus, narrower fingers can be used (Fig. 1, bottom).

2. As the number of busbars increases, less current flows in each busbar and ribbon; this reduces the resistive losses in the ribbon, and a narrower busbar (and ribbons) can then be used to reduce the ribbon shading.

3. The use of less material (silver paste and copper ribbons) can offer a significant saving.

Accordingly, the solar cell and the stringed solar cell should be optimized for finger width/height, number of fingers, number of busbars, busbar width and ribbon width, while considering the optimum performance at the module level. These parameters are optimized using simulation software and presented in the next section.

Halved-cell module

Another approach to improving the module performance is using halved-cell modules. Cutting cells in half is an effective way of decreasing the resistive power loss in PV modules, since this can reduce the amount of current flowing in each ribbon by half. Halved-cell modules have been reported by several researchers and PV module manufacturers: the method has already been applied by some major PV module manufacturers (Mitsubishi, REC, BP Solar) in their commercially available PV modules [10,11].

> "Halved-cell PV modules yield not only improved electrical performance but also better optical performance."

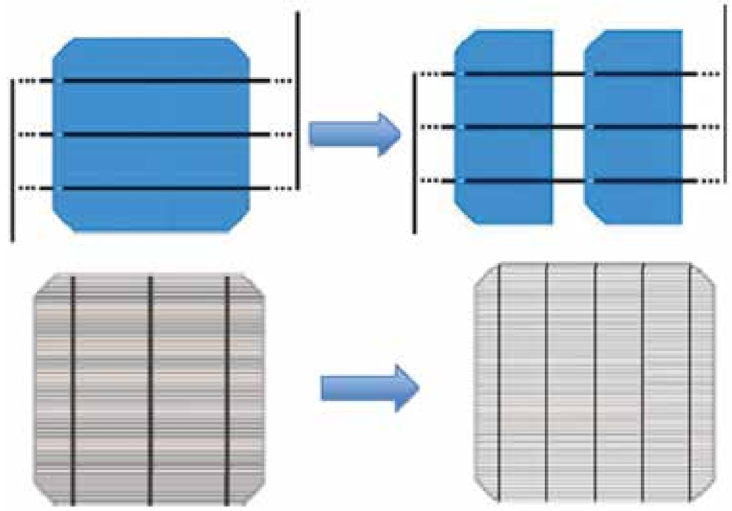

Figure 1. Schematics of half-cut and multi-busbar cell approaches.

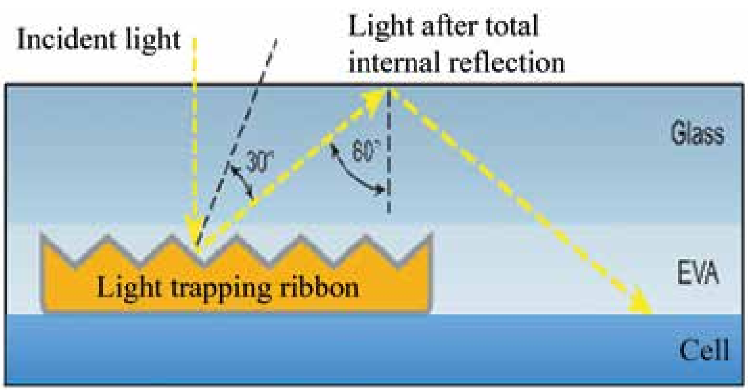

Figure 2. Light trapping in a PV module using LTR.

Fig. 1 (top) shows the schematics of two stringed half-cut solar cells. Halved-cell PV modules yield not only improved electrical performance but also better optical performance, resulting in higher currents compared with full-size cell modules. The higher module current is mainly due to the static concentration effect of light incident on the cell-gap region of the module, as described in Guo et al. [4] and Singh [9]; this effect, however, is not included in the current study.

Light-trapping ribbon

In a wafer-based PV module, most of the light incident on the conventional flat interconnecting ribbon is reflected back and escapes through the front glass. On the assumption of a ribbon reflectance of 100%, there is an optical loss of about 2.88% due to light reflection from the flat ribbon for a standard PV module with a 3-BB configuration and a ribbon width of 1.5mm. If the soldering ribbon is designed with a textured surface (such as a V groove), the light reflected by the ribbon will be at an angle to the module plane. If the groove height and spacing are optimized, it is possible that the light can be reflected at an angle greater than the total internal reflection angle for the glass–air interface. In this case, the light reflected at the ribbon will be totally internally reflected at the front glass–air interface and redirected onto the solar cells, thus increasing the module current generation potential. Such a ribbon can be termed a *light-trapping ribbon (LTR)* or a *light-harvesting string (LHS)* [5,12]. Fig. 2 shows the light path in a module with a textured ribbon (V groove).

Measurements and simulation results

Griddler, a 2D finite-element grid modelling software package developed at SERIS [13], was used to optimize the front-side metal grid for different numbers of busbars. The software simulates the I–V curves of the cell and the stringed cell (with ribbon) by calculating the voltage distribution throughout the cell; it considers all the electrical parameters of a solar cell (e.g. recombination properties and resistive components) as input to the model. For each number of busbars, the various metallization parameters – such as busbar width, number of fingers and finger width – that yield the highest module power are optimized. The power gains in all the different cases are calculated by comparing the performance with a standard 3-BB reference module with 1.5mm busbar widths. The finger width was kept constant at 45µm for all the different metallizations. The simulated cell parameters V_{oc}, I_{sc}, FF and efficiency for the 3-BB reference cell are respectively 632.9mV, 8.99A, 79.53% and 18.61%. Table 1 shows the simulation parameters used in the Griddler software to optimize the cell and module design.

Power gain and electrical performance of multi-busbar and halved-cell modules

Fig. 3 shows the simulation results for module efficiency/power gain for different numbers of busbars compared with a 3-BB full-cell module: it is seen that for a full-size cell module, a power gain of ~1.3% is achievable for a six-busbar (6-BB) configuration. This gain becomes greater if the multi-busbar approach is combined with the halved-cell approach: in total, a power gain of more than 4% is possible using a combination of the two approaches, as shown in Fig. 3 and Table 2.

In addition, Table 2 shows the optimized ribbon (and busbar) width for different module/cell configurations. The optimized values of busbar and ribbon also depend upon the ribbon availability and cost. Slight changes in the optimum width, however, will change the module power only marginally. For example, in a five-busbar (5-BB) full-cell module design, if a ribbon width of 0.9mm (busbar width 0.8mm) is used instead of an optimum ribbon width of 0.8mm, the module power from the simulation will be 267.2W (as compared with the 267.4W shown in the table). Thus, a ribbon width can be chosen on the basis of availability of the nearest possible width.

It should be noted here that the power gains presented in Fig. 3 do not include the gain due to the backsheet concentration effect resulting from the change in module design from full cell to halved cell. The power gains in the multi-busbar and halved-cell approaches mainly arise from improvements in the *FF* and I_{sc} of the module, as explained in the theoretical background section. The gain contribution due to an improvement in open-circuit voltage (V_{oc}) is minimal; this is mainly because of the reduction in semiconductor/metal recombination for less metal coverage. It should be noted here that the power gains from half-cut cell approaches for five and six busbars correspond to ribbon widths of 0.4mm and 0.3mm. In practice, however, the realization of such narrow ribbons will depend on the capability of the multi-busbar stringer, and this might reduce the achievable power gain. With the current teamtechnik stringer, a minimum ribbon width of 0.5mm can be used. Considering this limitation, the optimum half-cut design has 5-BB cells (0.5mm ribbon width) and a simulated module power of 274.9W.

Performance of PV modules using multi-busbar, half-cut cell and LTR technologies

If LTR is incorporated into the multi-busbar and half-cut cell approaches discussed earlier, the cell and module will have to be re-optimized accordingly. To find the optimum performance resulting from the use of LTR, the optical performance of this type of ribbon is first measured and quantified. This data is then used in Griddler to simulate the optimum parameters for the solar cells and modules. To measure and quantify the performance of LTR, external quantum efficiency (EQE) measurements are taken for single-cell mini-modules fabricated using LTR and standard ribbons. The EQE measurements are carried out on a number of points on the module area other than the ribbon, as shown in Fig. 4.

> “LTR can recapture more than 75% of incident light, whereas with normal ribbon this value is only ~4%.”

Fig. 5 shows the EQE measurements on different ribbon (standard ribbon and LTR) areas and on the module active area. The EQE measurements on the ribbons are normalized using the J_{sc} (calculated using EQE) of the mini-module. The results show that LTR can recapture more than 75% of incident light, whereas with normal ribbon this value is only ~4%. This corresponds to a net current gain of ~2% for a standard 3-BB module with a ribbon width of 1.5mm.

With the use of Griddler and the measured optical properties of LTR, the cell was modelled and optimized for a given busbar width for different numbers of busbars (four, five and six) and for full-cell and halved-cell designs. For the simulation, the cells were assumed to be fabricated from the same wafer (differing only in metallization); hence, the cell/module parameters used were the same as those for the baseline 3-BB cell and module described in the previous section. Fig. 6 shows the simulated module power and performance gain for various module designs.

The corresponding LTR widths and cell busbar widths are given in Table 3. From the simulation results obtained, it can be seen that if a 6-BB full-cell is used in combination with LTR, a performance gain of ~3.6% can be achieved. If the halved-cell approach is also used in this combination, a total performance gain of more than 5% can be achieved.

Experimental results and discussion

To experimentally determine the power gain for a large-size PV module with the different approaches discussed earlier, four different types of PV module were fabricated. The solar cells used in this study were metallized as per optimized simulated screen design. For all of the metallization designs, pre-metallized cells from the same batch were used. A state-of-the-art teamtechnik stringer in the PV module lab at SERIS was then used to produce strings for the

Parameter	Value
Emitter sheet resistance	80Ω/sq.
Finger/busbar sheet resistance	3Ω/sq.
Contact resistance	2.0mΩ·cm^2
Finger width	45µm
J_{01} (passivated area)	460fA/cm^2
J_{01} (metal contact)	960fA/cm^2
J_{02} (passivated area)	20nA/cm^2
J_{02} (metal contact)	50nA/cm^2
Busbar width	variable (0.2mm–1.5mm)
Ribbon width	variable (0.3mm–1.7mm)
Ribbon thickness	0.2mm
Ribbon resistivity	1.728×10^{-8}Ω·m

Table 1. Parameters used for front-grid optimization using Griddler simulations.

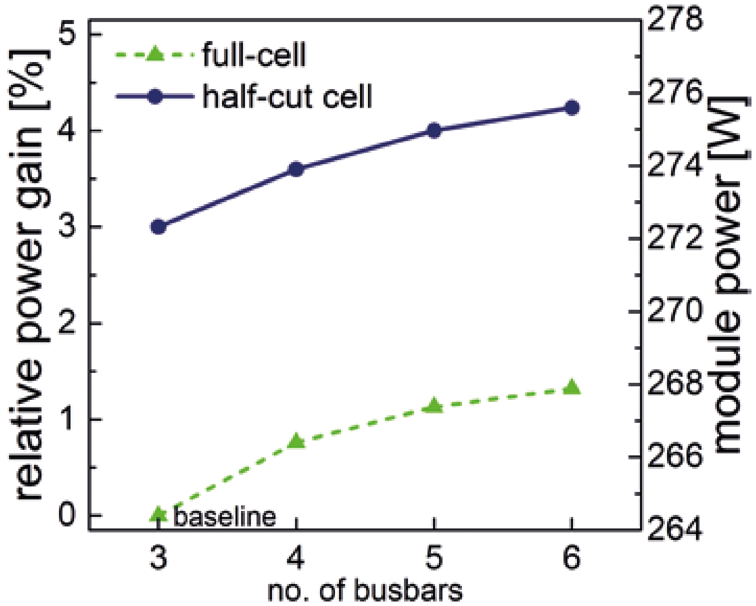

Figure 3. Simulation results for multi-busbar modules with full and halved cells. (A 3-BB full-cell module was chosen as the reference.)

Module type	Cell busbar width [mm]	Ribbon width [mm]	Simulated 60-cell module power [W]	Performance gain [%]
Baseline (3-BB full-cell)	1.5	1.5	264.4	–
4-BB full-cell	0.9	1.0	266.4	0.77
5-BB full-cell	0.7	0.8	267.4	1.13
6-BB full-cell	0.6	0.7	267.9	1.32
4-BB halved-cell	0.5	0.6	273.9	3.60
5-BB halved-cell	0.3	0.4	275.0	4.00
6-BB halved-cell	0.2	0.3	275.6	4.24

Table 2. Simulated module power and performance gain for multi-busbar and halved-cell approaches.

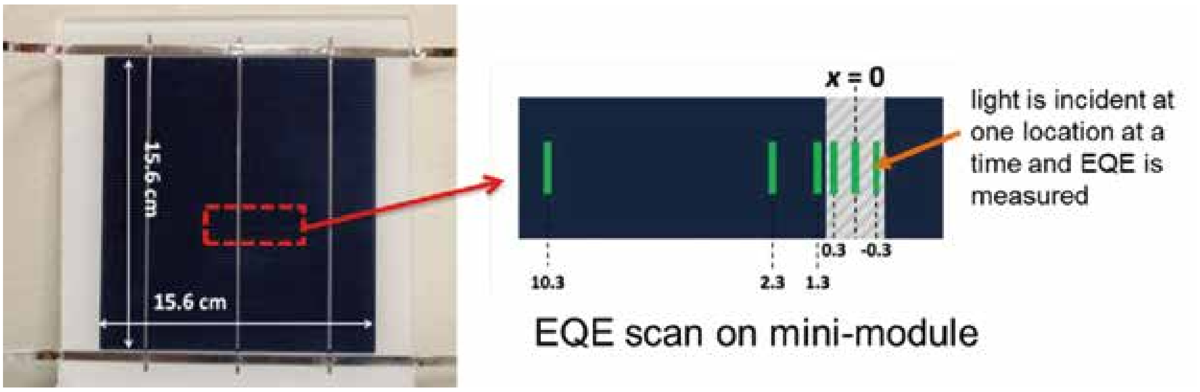

Figure 4. Measurements schemes for LTR and standard flat ribbon in a mini-module using a spot-area illumination spectral-response measurement system.

different cell designs, i.e. three, five and six busbars, with full and half-cut solar cells, as given in Table 4. This stringer can produce strings using 0.5mm-wide ribbon with a high accuracy of ribbon alignment to the solar cell busbar.

To fabricate halved-cell modules, the solar cells were cut in half using a nanosecond laser at SERIS's solar cell lab; the same material and processes were used to fabricate all these modules. The *I–V* characteristics of all the PV modules were then measured using a h.a.l.m. sun simulator (class A$^+$A$^+$A$^+$) at SERIS's PV module lab. The cell gaps and string gaps for full-cell modules were kept at 3mm and 5mm respectively. The halved-cell modules were produced with a cell gap of 2mm and a string gap of 5mm. LTRs from Schlenk [12] were used in this study; these were also characterized using EQE measurements on single-cell mini-module samples as described in the previous section. Photographs of sample modules are shown in Fig. 7.

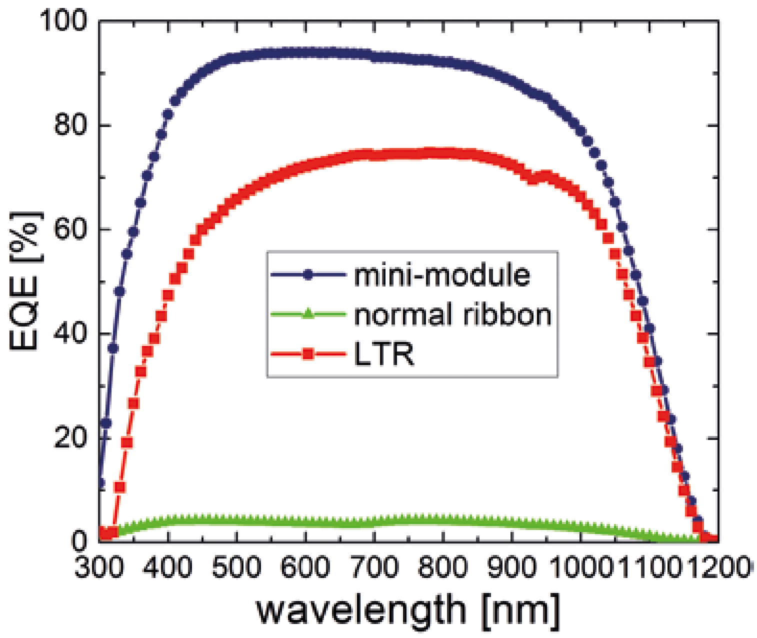

Figure 5. Measured EQE for the illumination points on LTR and normal soldering ribbon, and on the module active area (without ribbons).

"The simulation and experimental results show that for the 6-BB with LTR design, the module performance can be improved by ~3.6%."

Table 4 lists the measured *I–V* parameters of the four modules, and Fig. 8 shows the performance gain of these modules relative to a 3-BB full-cell reference module. In the figure the performance gains obtained from the measurements of the experimental module samples are aligned with the corresponding simulation results presented in the previous section. The additional differences between full-cell and half-cell modules in comparison to the simulated results are mainly due to the optical gain from the backsheet static concentration effect, which was not considered in the simulation study.

The simulation and experimental results show that for the 6-BB with LTR design, the module performance can be improved by ~3.6%. The half-cut cell concept can be combined with the multi-busbar and LTR concepts in order to achieve a performance gain of more than 5%. This, however, will require additional cost associated with cell cutting, and potentially more stringers will be needed to produce the same MW of module power. Thus, the viability of half-cut concepts requires further study by considering the additional CapEx and cost.

Another interesting conclusion can be drawn when the power gains are compared with the results in the literature for multi-wire technology. A multi-wire module can enhance performance by ~1.76% compared with a standard 3-BB module [7]; however, the multi-wire module requires a completely new stringer, and the wire material will impose additional cost on the module. It is therefore more favourable to use a 6-BB stringer together with LTR, since this combination can provide the required enhancement to module performance without much investment and major modifications to the module manufacturing facilities.

Cost-benefit analysis

In an earlier section, the benefit of multi-busbar and LTR from a performance point of view was explored. Ultimately, module manufacturers care about the cost of the module; thus, a cost analysis is necessary in order to evaluate the technologies with regard to their economic feasibility. This section presents a cost analysis, taking into consideration both the silver saving because of different metallization techniques and the cost of LTR. The objective of the analysis is to achieve a minimum \$/Wp cost of the PV module.

For the cost analysis, the relative costs of module components for a standard large-size PV module are required. With information from a market survey conducted by SERIS and the available information from module material manufacturers, the relative cost contributions of the module components for standard 60-cell PV modules were estimated and are given in Table 5. In addition to the information in Table 5, the silver cost is assumed to be 4.4% of the total solar cell cost in these cost calculations.

Now, by estimating the metal fraction for different cell designs and calculating the amount of ribbon required for the large-size module, it is possible to access the relative change in the module cost with respect to the baseline module (3-BB). Fig. 9 shows the relative change in the cost for different module designs with multi-busbar and LTR enhancements compared with a standard 3-BB module. It is interesting to note that, despite the higher power gain resulting from the LTR approach (discussed earlier), the cost reduction potential is limited for these module types compared with the multi-busbar approach; this is mainly because of the additional cost of LTR, whereas the increase in silver consumption with the use of wider busbars is only marginal. From the cost analysis in Fig. 9 it can be observed that the cost of the module with LTR does not change significantly when moving from six busbars to four: a 4-BB module with LTR can provide a potential

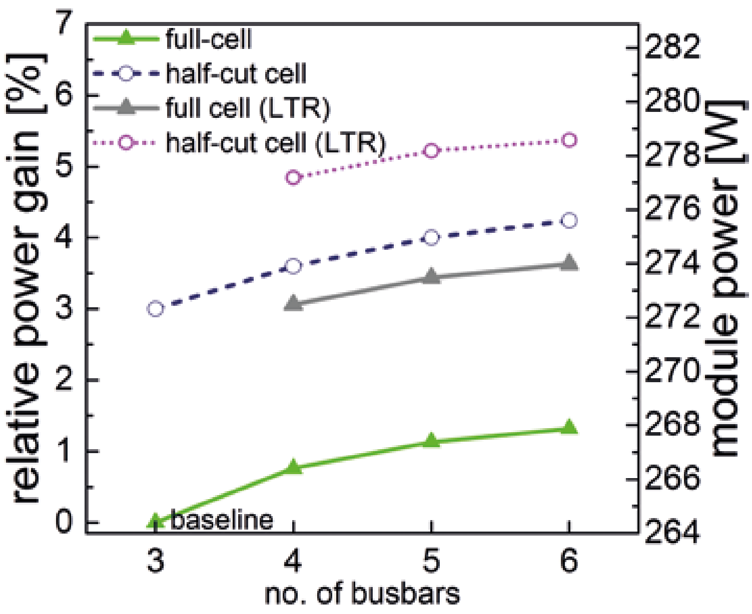

Figure 6. Simulated power gain and module power for multi-busbar, full-cell and LTR designs. (A 3-BB full-cell module was chosen as the reference.)

Module type	Cell busbar width [mm]	LTR width [mm]	Simulated module power [W]	Performance gain [%]
4-BB full-cell	1.4	1.5	272.5	3.06
5-BB full-cell	1.2	1.3	273.5	3.44
6-BB full-cell	1.0	1.1	274.0	3.63
4-BB halved-cell	0.7	0.8	277.2	4.84
5-BB halved-cell	0.6	0.7	278.2	5.22
6-BB halved-cell	0.4	0.5	278.6	5.37

Table 3. Simulated module power and performance gain using LTR for different cell/module types.

Module type	Front-side BB width [mm]	Ribbon width [mm]	I_{sc} [A]	V_{oc} [mV]	*FF* [%]	Power [W]	Relative power gain [%]
3-BB full-cell	1.5	1.5	8.922	37.82	76.72	258.9	–
5-BB halved-cell	0.4	0.5	9.184	37.97	78.13	272.5	5.25
5-BB full-cell with LTR	1.1	1.2	9.152	37.89	77.35	268.2	3.6
6-BB full-cell	0.5	0.6	9.013	37.95	76.91	263.1	1.6

Table 4. Measured electrical parameters of four large-size PV modules.

Figure 7. Photographs of fabricated sample PV modules (5-BB LTR, 6-BB, 5-BB halved-cell, 3-BB).

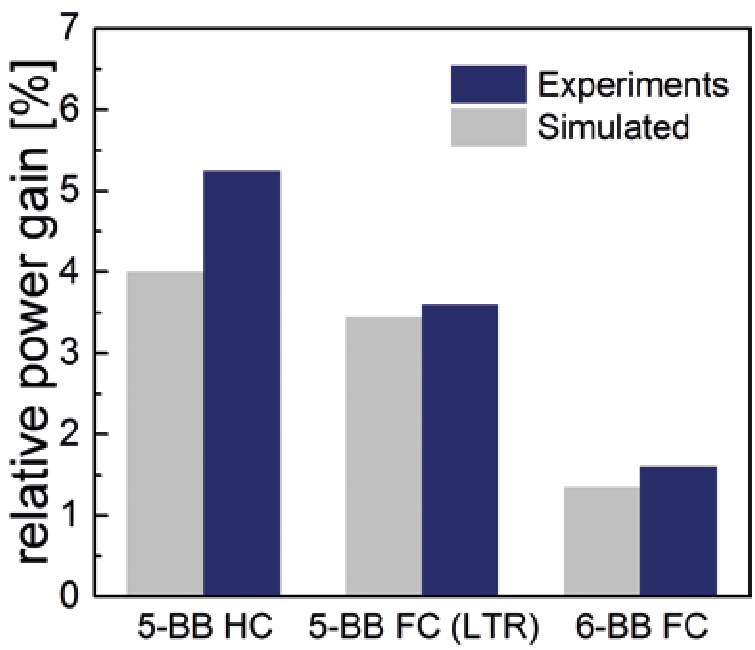

Figure 8. Simulation and experimental power gains for different PV modules fabricated at SERIS. (A 3-BB full-cell module was chosen as the reference.)

cost reduction of ~2.2%, which is only slightly lower than that for a 6-BB module. Notwithstanding the additional cost of LTR, this technology is very effective for high-power premium modules, where the main focus is to achieve maximum power.

Conclusion

With the use of the multi-busbar approach together with LTR and half-cut cell technologies, a significant improvement in module performance is possible. Stringers such as the one from teamtechnik are currently available on the market and can fabricate the strings using half-cut and LTR technologies with four, five or six busbars. The simulation and experimental results obtained show that an improvement of ~3.6% in module performance is possible with a 6-BB and LTR approach; with the additional use of the half-cut concept, this gain is further increased to 5.3%.

> "With LTR and a 4-BB module, a cost reduction of ~2.2% is possible."

An economic analysis was performed for the multi-BB and LTR approaches. The cost-benefit analysis shows that the multi-busbar technique has the potential to reduce the module cost by ~2.5%. Because of the higher cost of LTR, however, the power gain in this case does not always translate to a reduction in module cost. Nevertheless, with LTR and a 4-BB module, a cost reduction of ~2.2% is possible. With all the approaches combined, a high-power premium module can be realized, although at additional cost.

PV Modules

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	Solar cells	Glass	EVA	Backsheet	Ribbon	Busing ribbon	Frame	Other
Cost contribution [%]	70.8	5.1	3.3	7.8	1.5	0.4	6.8	4.3

Table 5. Distribution of the component costs for a 60-cell silicon PV module.

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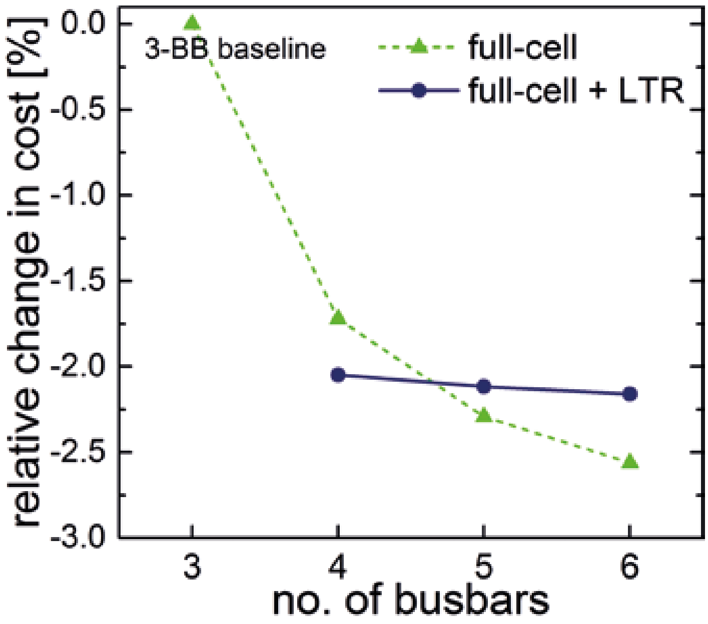

Figure 9. Cost-benefit analysis for module designs using multi-busbar and LTR approaches (full-cell). (A 3-BB module is chosen as the reference.)

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Jai Prakash Singh received his Ph.D. in electrical and computer engineering from NUS. He works as a research scientist with SERIS at NUS, and has more than 10 years' experience in solar PV. His research focuses on the characterization, loss analysis and optimization of c-Si solar cells and modules.

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