Investigation of cell-to-module (CTM) ratios of PV modules by analysis of loss and gain mechanisms

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ABSTRACT

The output power of a solar module is the sum of the powers of all the individual cells in the module multiplied by the cell-to-module (CTM) power ratio. The CTM ratio is determined by interacting optical losses and gains as well as by electrical losses. Higher efficiency and output power at the module level can be achieved by using novel ideas in module technology. This paper reviews methods for reducing different optical and electrical loss mechanisms in PV modules and for increasing the optical gains in order to achieve higher CTM ratios. Various solutions for optimizing PV modules by means of simulations and experimental prototypes are recommended. Finally, it is shown that designing PV modules on the basis of standard test conditions (STC) alone is not adequate, and that, to achieve higher CTM ratios by improving the module designs in respect of environmental conditions, an energy yield analysis is essential.

Introduction

The processing of solar cells into modules leads to different physical power loss and gain mechanisms in the stack. The optical losses result from reflection and absorption in the glass and encapsulant, and the electrical losses are caused by the Joule heating effect in module interconnections. Optical gains are realized through back reflections of light from the backsheet through the cell spacing, from solar cell metallization and connecting tabs, and from the solar cell surface inside the cover stack [1–5].

The ratio of module power to cell power, multiplied by the number of cells integrated in the module, is defined as the *cell-to-module (CTM) power ratio*. This factor quantifies the general loss/gain percentage in a PV module [6], and its importance can be explained by means of an example. The efficiency of some of the top solar cells recently launched on the market is about 21.25±0.4% for multicrystalline solar cells, while the corresponding PV module incorporating these cells demonstrates an efficiency of 19.2±0.4% [7]. This corresponds to a reduction in module efficiency of almost 2%$_{abs}$, or a CTM ratio of 90%, which equates to almost 18 years' R&D work on improving the efficiency of multicrystalline solar cell technology [7,8].

According to the International Technology Roadmap for Photovoltaics [6], with advances in PV and module technology it is expected that CTM ratios of over 100% will be achieved by reducing the electrical and optical losses and increasing the optical gains at the module level, as seen in Fig. 1. (Note that 'CTM' is still occasionally used to refer to cell-to-module *power* losses; however, since the losses are nowadays expected to be 0% and below, the CTM power ratio is more widely used.)

This paper reviews different methods for increasing the CTM ratio of PV modules by modifying module integrations and employing different module designs. Optical effects in PV modules are discussed, along with possible solutions for reducing the optical losses and increasing the gains. Also presented are various modifications of module interconnections and connecting tabs in order to decrease electrical losses by means of alternative measurement and simulation methods. Furthermore, the impact of environmental conditions

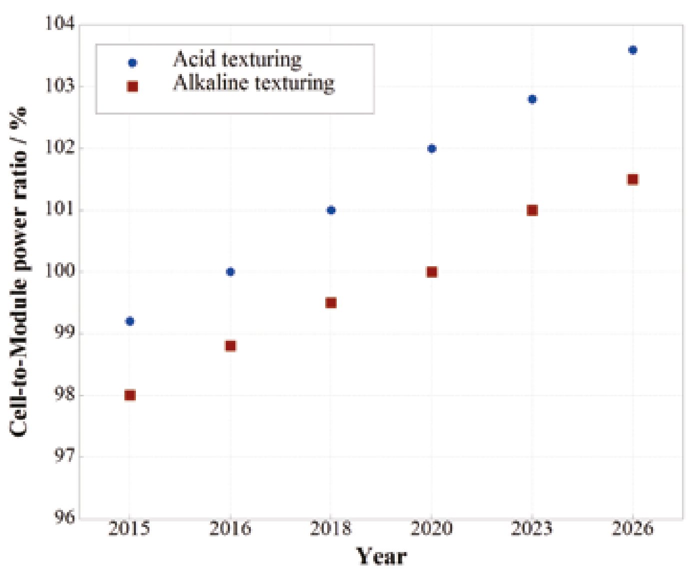

Figure 1. Expected trend of the CTM power ratio over the next 10 years [6].

on module performance is analysed, and possible solutions and tools are proposed for increasing the CTM ratios with regard to different locations and climates.

"A higher CTM is achievable by reducing unavoidable electrical and optical losses and by enhancing direct and indirect optical coupling gains."

Power gain approaches

Basically, a higher CTM is achievable by reducing unavoidable electrical and optical losses and by enhancing direct and indirect optical coupling gains. Electrical losses in the module are ohmic losses due to the interconnection in the module and bypass diodes in the case of shading conditions. Optical losses are caused by light reflection and absorption in the front stack of module materials, as well as by light incidence on inactive module areas, such as the module perimeter, cell interspaces and top contacts. Direct optical coupling gains result from improved index matching at the front cell interface after lamination. Indirect optical coupling gains can be obtained by redirecting light from inactive module areas to the cell.

Fig. 2 shows the relevant loss and gain mechanisms that occur in the different regions of a typical c-Si solar module, i.e. in the front layer stack (mechanisms 1–5), in the cell interspace/module border areas (6 and 7), on the top contacts (8 and 9), and in the electrical interconnection (10). The indicated numbered effects and possible related CTM improvements are discussed in the following subsections.

A suitable method for predicting the total power of a module has proved to be a sequential consideration of the mechanisms, where a certain loss/gain factor is calculated for each effect [3]. In the determination of the individual factors, the whole system needs to be considered: an example of this is that the reflection loss at the glass/encapsulant interface is (as will be explained below) determined by the glass, the encapsulant, and the spectrum hitting that interface, as well as by the spectral response of the present cell.

In module evaluation and design, the optical and electrical interactions between the different module components need to be considered. For the top-contact design in particular, the optical and electrical effects influence each other; for example, the optical shading losses of the front contacts are reduced by using smaller tab widths, but, at the same time, smaller tabs cause higher resistive losses. The electrical losses in the interconnection should always be taken into account. In the optimization of the efficiency of a module, the product of all loss/gain factors has to be maximized. A cost–benefit analysis, however, is also essential, especially in the case of commercial modules.

Optimization of the module stack (mechanisms 1–5)

On a light path through the front layers of a module, the targeted optical losses for reduction are (with reference to Fig. 2) the reflection at the glass/air interface (1), the absorption inside the glass (2), the reflection at the glass/encapsulant interface (3), and the absorption inside the encapsulant (4). With regard to the CTM, the reflection at the encapsulant/cell interface (5) is usually a gain. This is due to the fact that a larger fraction of light is coupled into the cell surface after lamination, because the high refractive index of the cell ($n_{SiN} \approx 2$ and $n_{Si} = 3.8$ at $\lambda = 680$nm) better matches that of the encapsulant materials ($n_{encapsulant} = 1.48 \ldots 1.50$ at $\lambda = 680$nm) than that of air ($n_{air} \approx 1$).

The change in light intensity at the reflecting interfaces under consideration and inside the corresponding absorbing layers can be calculated using the Fresnel equations [9] if the optical spectroscopy data

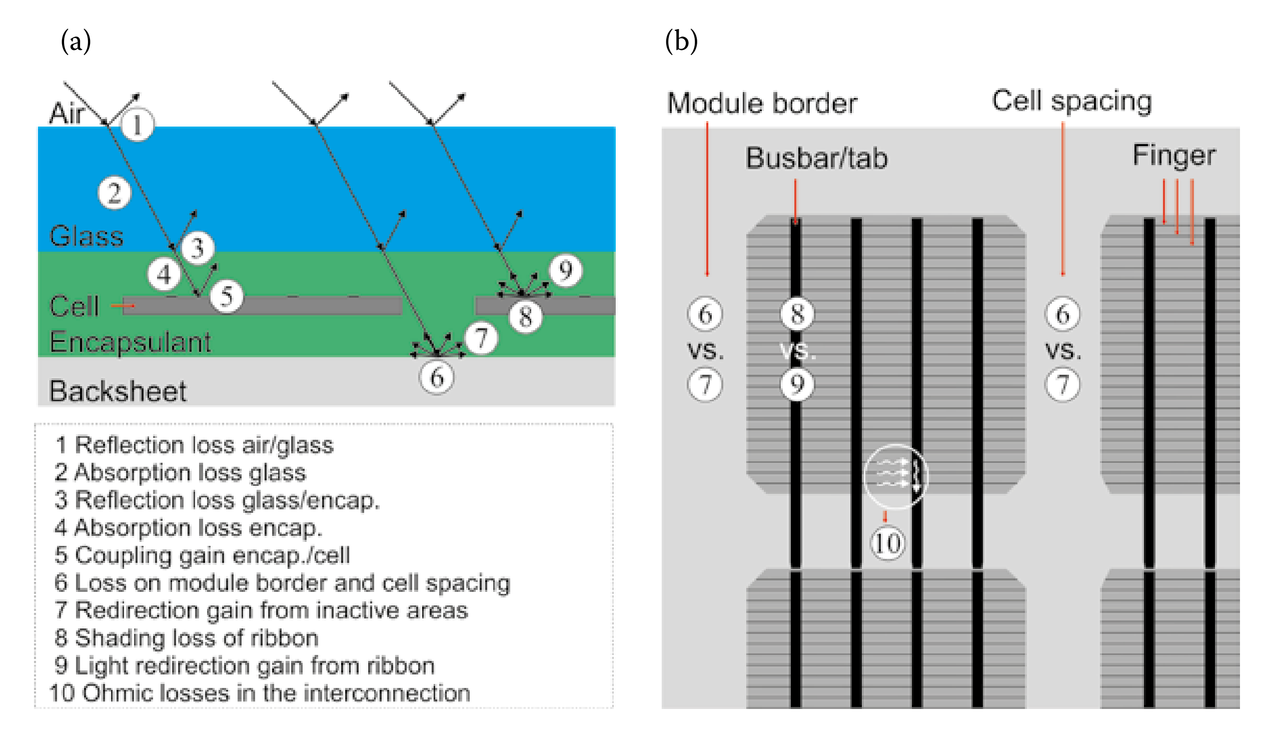

Figure 2. Schematic cross section (a) and top view (b) of a typical crystalline Si-based PV module, showing the different loss/gain mechanisms described in the text.

of the material are known. In the case of thin layers, interference effects have to be considered in an electric field description; this can in principle be done analytically, but is usually calculated numerically by the so-called *transfer-matrix method* [10]. If the effects of structured interfaces or regions need to be determined, it might be necessary to perform numerical simulations – for example, finite element calculations.

Considering the standard case of vertical incidence on a planar interface between layer *j* and layer *j+1*, the Fresnel equations can be simplified, and the reflection coefficient, given by the ratio of reflected and incoming intensities, is then:

$$R_{\theta=0^\circ} = \frac{(n_{j+1} - n_j)^2}{(n_{j+1} + n_j)^2} \quad (1)$$

Correspondingly, for a simple air/Si interface a large amount of light intensity R = 35% (see values above) is lost. Theoretically, this loss can be reduced to about 10% by the distribution of the large refractive index difference Δn over several smaller steps.

Materials with optimal refractive indexes, however, are not available. Although a very good index matching between glass and encapsulant is possible, in the case of the other interfaces (i.e. air/glass and encapsulant/Si) anti-reflection (AR) coatings or light-trapping structures are the best options for reducing reflection losses.

The integral reflection loss at the air/glass interface (mechanism 1) can be reduced from about 4% to below 1% by introducing a single AR layer. A popular AR layer for glasses is nanoporous SiO_2, since it has the required low (effective) refractive index n, the specific value of which can be designed by the volume fraction of the pores.

The optimum refractive index of an AR layer is intermediate to those of the materials on either side, i.e. $n_{AR} = (n_j \times n_{j+1})^{1/2}$. Its optimum thickness is $d = \lambda/(4 \times n_{AR})$, leading to zero reflection at the design wavelength λ by destructive interference. Of course, multilayer AR coatings can suppress reflection over a broader spectral range. However, with regard to the achievable additional efficiency gain, the added costs of multilayer coatings have to be taken into account for the economic production of solar modules.

The absorption loss inside the glass (mechanism 2) can be minimized by a proper choice of mineral glass, such as the extra-clear, low-iron, soda-lime silica glass. Besides the glass composition (transition metal ion impurities cause absorption losses in the relevant spectral range, and network modifiers determine the UV absorption edge), the glass quality (glass defects cause scattering losses) is of relevance.

The reflection loss at the glass/encapsulant interface (mechanism 3) can easily be reduced to below 10^{-3}, since suitable encapsulant materials with the same refractive index as glass ($n_{glass} \approx 1.5$ at λ = 680nm) are available (EVA, PVB, TPSE – all having a refractive index between 1.48 and 1.5 at λ = 680nm).

The absorption loss inside the encapsulant (mechanism 4) is more critical. Because of its reactivity, EVA is usually doped with UV blockers, causing the UV-absorption edge of the EVA to already set in at 380nm. Since such UV protection is not necessary for PVBs and silicones, they provide much better UV transmission.

From an optical optimization point of view, when choosing an encapsulant the index matching to the glass is more important than index matching to the cell surface. The reflection at the encapsulant/Si interface can be more effectively influenced by the surface texture and the silicon nitride AR layer of the cell. Thus, an improvement related to mechanism 5 requires an optimization at the cell level, which is not discussed further in this paper.

In general, the effects of different module materials depend on the particular set-up. The loss factor, which is the relevant quantity in module design, is a weighted total integral intensity loss over the relevant spectral range. The integral is weighted with the spectrum incident on the corresponding layer and the spectral response of the solar cells under consideration. In Fig. 3(a) the combined weighting function, i.e. the product of both functions, is shown for an irradiated AM1.5g sun spectrum and selective emitter (SE) cells with a high UV spectral response. By means of this weighting, the fact that the module materials need to be optimized with respect to the spectral distribution of the available (and also convertible) light intensity is taken

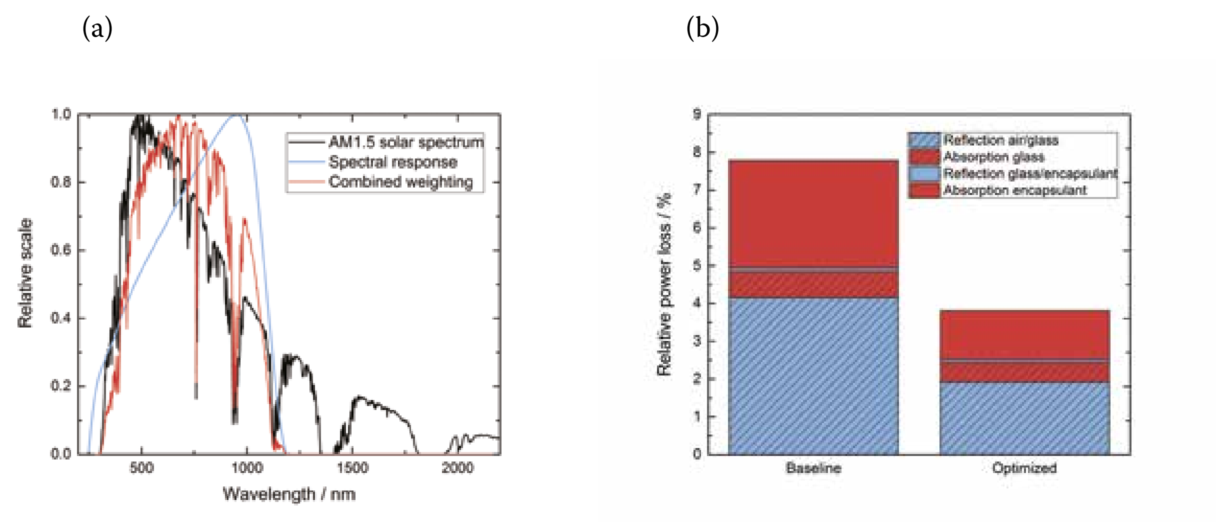

Figure 3. (a) Irradiated AM1.5g solar spectrum [12], spectral response function of selective emitter (SE) cells, and resulting weighting function. (b) Relative power losses due to various optical processes in the front stack of a baseline module compared with a module optimized with an AR coating on glass, thinner glass and high UV transmittance encapsulant [11].

into account. In the example given next, the performance of the material is relevant between approximately 300 and 1100nm, where the design wavelength should be at about 675nm, in other words at the maximum of the combined weighting function.

Example: Effects of AR coating, thinner glass and high UV transmission encapsulant
To illustrate the effects of various innovative technologies, in the following example the different loss factors for mechanisms 1–4 are determined for a baseline and an improved solar module. Both modules are prepared with SE solar cells. In essence, the baseline module is built with standard solar glass and EVA encapsulant, whereas glass with an AR coating and reduced thickness (2mm instead of 3.2mm) and PVB encapsulant is used for the improved module. The experimental investigations of the modules and the module materials used are presented in Schneider et al. [11].

Here, the factors are calculated with the combined weighting function given in Fig. 3(a) by using the optical transmittance and reflectance spectra of individual and combined module materials. The resulting power losses are summarized in Fig. 3(b). The relative power loss of mechanisms 1–4 is about 8% in total for the baseline module investigated. The largest contribution to the power loss, being about 4%, stems from the reflection at the air/glass interface. By introducing an AR layer onto the glass, this loss could be significantly reduced for the optimized module, as seen in Fig. 3(a). The difference in the absorption loss originates from the reduced glass thickness, but the effect is small, since the low-iron glass utilized has only minor residual absorption losses. The reflection loss at the glass rear-side interface is even smaller, because the refractive index of both encapsulant materials matches very well that of the glass, resulting in the reflection loss at the glass/encapsulant almost vanishing for both modules.

The absorption loss inside the encapsulant, on the other hand, has a large impact, but is significantly reduced when using PVB instead of EVA. Here, the above-mentioned higher UV transmittance of PVB basically explains the positive effect; a larger part of UV light reaching the cell can be used for electrical power generation. Especially in the case of the SE cells considered here, this effect is significant, because SE cells yield a relatively good UV response. In total, the relative power loss is reduced from about 8% to below 4% by all the innovative technologies used in the improved module. The results could be verified by means of flasher measurements on mini-modules and on standard-size modules.

Optimization of cell interspaces and module border areas (mechanisms 6–7)

A portion of the incident radiation on a module hits the cell interspaces and module borders first rather than the solar cells themselves, and thus cannot directly be used for power generation (mechanism 6). The absolute efficiency of the solar module decreases in proportion to the size of those inactive areas. The corresponding optical efficiency loss can be reduced by minimizing these areas and by a proper choice of module geometry and cell format; for example, full-square wafers yield a higher fraction of active areas on a module than pseudo-square or round wafers.

The ability to reduce the distance between the cells, however, is limited. The cell space within a string is mainly limited by mechanical stress caused by tabs between the front contact of one cell and the back contact of the neighbouring cell. A minimum distance between strings is basically imposed because of positioning-accuracy challenges and lamination-induced shrinkage of the encapsulant, which can bring adjacent strings into contact and thus cause short circuits. With regard to the dimensioning of a module, a compromise between cost and benefit needs to be found.

In this context, it must be in particularly borne in mind that these inactive areas do not negatively affect the module power. On the contrary, the partial redirection of light from inactive areas to the cell (mechanism 7) provides an extra current and thus additional power. This gain can be achieved by means of reflections from the inactive areas, since a part of that light is reflected back at the glass/air interface and thus partially redirected to the cell. This light-recycling effect is a decisive step towards the ambitious goal of achieving a CTM well above 100%.

Example: Effect of a white backsheet
As an example, for state-of-the-art white backsheets it has been shown, by light-beam-induced current measurements (LBIC), that illumination of the area next to a cell generates typically 20% of the short-circuit current obtained from direct cell illumination. If the space between neighbouring cells is also considered, the relative amount is doubled to 40%. For a typical cell efficiency of 18%, the efficiency of the cell interspaces is thus greater than 7%. In the case of a standard module with 5mm cell spacing, the additional total cell interspace area with 7% efficiency is about $0.1m^2$; this corresponds to approximately 3% more power [13].

Optimization of the top-contact design (mechanisms 8–9)

Cell shading due to the front-side metallization (mechanism 8), i.e. fingers and contacting tabs, can be reduced by minimizing the widths of these contacts; however, series resistance losses increase with smaller contact cross sections. Thus, an optimization with regard to these

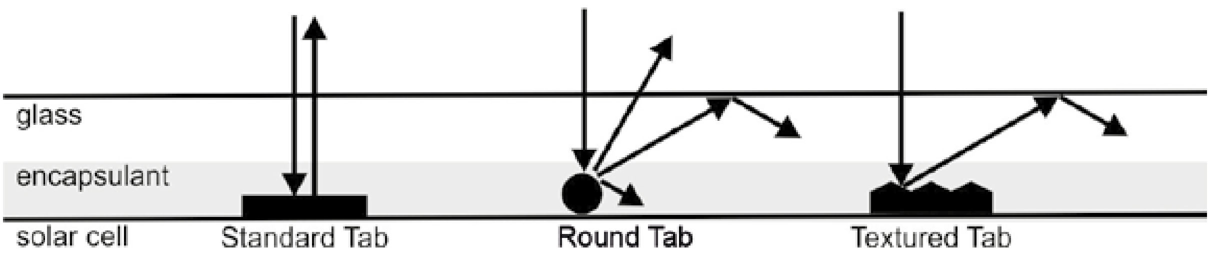

Figure 4. Schematic of the reflection paths produced by various tab technologies [13].

PV Modules

optical and electrical losses would suggest that contacts with high aspect ratios (i.e. having small widths and large heights) are necessary. However, with high aspect ratios come stiffer tabs, which can induce cell breakage during module processing and operation [14].

One option for improving the CTM is to obtain an indirect coupling gain on the top contacts (mechanism 9) by using improved tab geometry. In Fig. 4 the light reflection paths following vertical incidence are shown schematically for three different tab geometries.

Standard tabs reflect normal incident light straight back and thus do not generate a gain. For *round tabs*, depending on the region where light hits the wire, different cases are possible: hitting the first region, light can be reflected sideways towards the cell; entering the second region, light is reflected to the glass/air interface at such an angle that it is totally reflected back to the glass. The reduction in the effectively shaded area of a wire can be easily calculated and is 70.7% for the first region and 35.7% for the second [15]. In the third case, light hitting this region is either reflected back through the glass or partially reflected at its surface, depending on the specific angle. *Textured tabs* are designed in such a way that they reflect vertical incident light sideways so that it reaches the glass/air interface at angles greater than the critical angle for total internal reflection, and is thus redirected to the cell.

Example: Effect of light-harvesting strings
Turek and Eiternick [5] and Schneider et al. [11] compared modules built with light-harvesting strings (LHS, textured tabs made by Schlenk) and without them: LBIC measurements taken on both modules are presented in Fig. 5. The results indicate that illumination on a standard tab produces 5% of the short-circuit current generation of the actual cell, whereas for LHS this proportion is increased to 75%. This extra current means that the total current and power of the investigated module is enhanced by 3%, a value that is in agreement with directly measured short-circuit currents, where an enhancement of 2.5–3% was found.

Reduction of electrical losses in the interconnection (mechanism 10)

Electrical losses at the module level are mainly due to the losses in the cell and string interconnections (mechanism 10). Cell interconnections cause optical losses by partially covering the active area of the solar cell, while electrical losses result from the current passing through the tabs [3,4]. Advances in module technology are expected to optimize the optical and electrical losses in order to achieve higher CTM power ratios.

Electrical losses decrease by increasing the tab width, whereas optical losses increase linearly with increasing tab width. The optimum tab width for harvesting maximum power should therefore be determined by considering both electrical and optical losses. Moreover, the electrical losses are related to the square of the current passing through the tabs; thus by changing the module design and decreasing the operating current of the solar cells, the electrical losses can be significantly reduced [2,4]. The use of cut solar cells in combination with a rearrangement of the interconnection designs is a good way of reducing electrical losses and increasing the CTM ratio [4].

“PV modules with half-size cells demonstrate better performance than conventional PV modules because of the higher optical gains and lower electrical losses.”

Example: Half-cell modules
PV modules with half-size cells demonstrate better performance than conventional PV modules because of the higher optical gains and lower electrical losses [16,17]. According to the experiments performed on monocrystalline cells by Hanifi et al. [4] and Eiternick et al. [18], when solar cells are cut in half the efficiency of the cells slightly decreases, by about 1.1%$_{rel}$, because of the laser-scribed edges. As illustrated in Fig. 6, the measured full-size cells have an average efficiency of 19.4%, and the half-size cells exhibit a lower efficiency after the laser-cutting process. The reduction in efficiency, however, is offset after the fabrication of one-cell modules: half-cell modules demonstrate 19.1% efficiency, which is 0.7% higher than in the case of full-cell modules. These results explain the 94.8% CTM ratio for full-size cells and 98.4% for half-size cells, when the losses due to the laser-scribing process are considered [4].

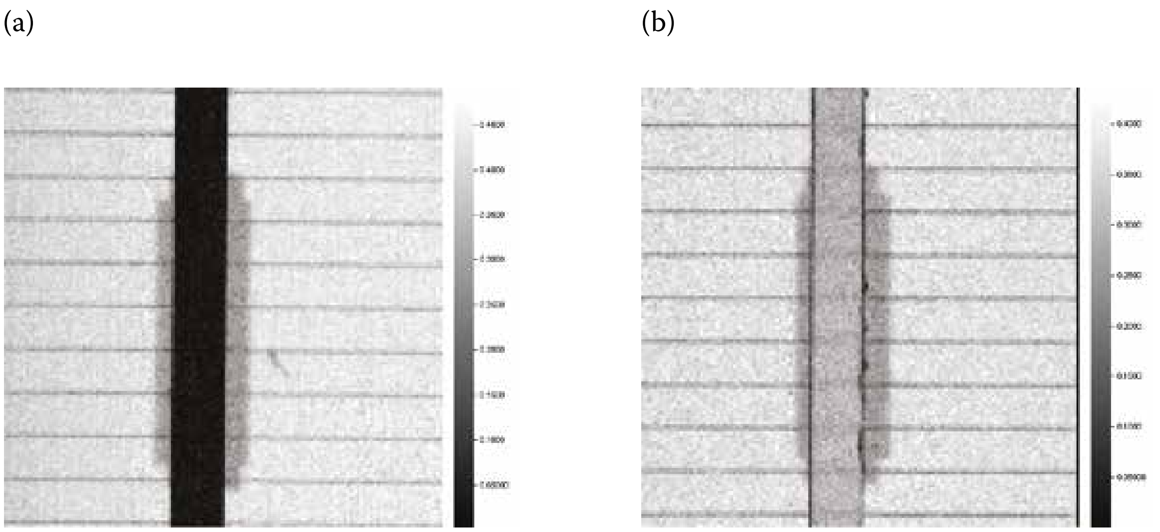

Figure 5. Light-beam-induced current images: (a) without light-harvesting strings (LHS); (b) with LHS. The current generation from the tab regions is significantly improved [11].

Half-cell modules generate half the current of full-cell modules; therefore, the electrical losses of the connections of half-cell module are one-quarter those of full-cell modules [17]. New module designs require a rethinking of the tab dimensions when optimizing the electrical losses in module interconnections. Fig. 7 shows the simulation results for the optical, electrical and overall losses of a module with two half-size cells, and for a module with one full-size cell, in respect of different tab widths at standard test conditions (STC). The cells are monocrystalline with three busbars, and their electrical properties are measured before and after the module fabrication. At STC the optimum tab width for standard cells is 1.7mm. By cutting the solar cells in half, the power loss decreases by 2.14%. By reducing the tab width of half-cell modules to 0.8mm, 0.92% more power can be gained. It can be concluded that the optimum tab width for half-cell modules is around 0.8mm, which is almost half the optimum tab width of the full-cell layout. The use of a narrower tab width for a half-cell layout therefore leads to an increase in the CTM ratio and to a reduction in material consumption [4].

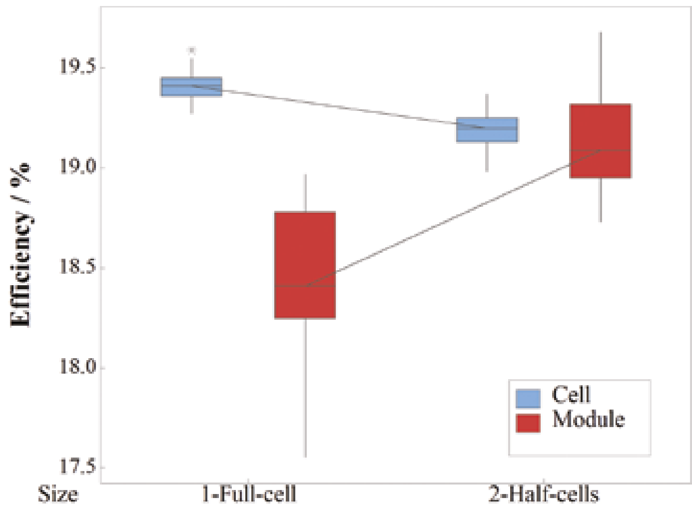

Figure 6. Efficiencies of half-cell and full-cell concepts at the cell and module levels. Losses due to the laser-cutting process are compensated for at the module level [4].

It should be noted that the extra optical gain resulting from the additional cell spacing in half-cell modules is not included in the simulation results.

From power to energy

Spectrally resolved CTM

Higher CTM ratios can be achieved by using different technologies in module integration. Solar cell technology, as the most important part of module integration, can play a significant role. Monocrystalline solar cells have alkaline-based textures with good optical properties which lead to better quantum efficiency compared with multicrystalline solar cells with an acid-based texture – see Fig. 8(a). The lower texture quality of multicrystalline cells brings with it higher reflection losses and thus decreased initial cell efficiency in air. A higher coupling gain when embedded into a module is therefore made possible, which yields a higher CTM ratio, especially in the UV and near-IR ranges, as a result of indirect optical coupling of the reflected light. This becomes evident when the external quantum efficiency (EQE) of mono-Si and multi-Si cells and modules are compared, as shown in Fig. 8(b).

“It is important to understand the loss mechanisms at different irradiation levels, especially low-light conditions.”

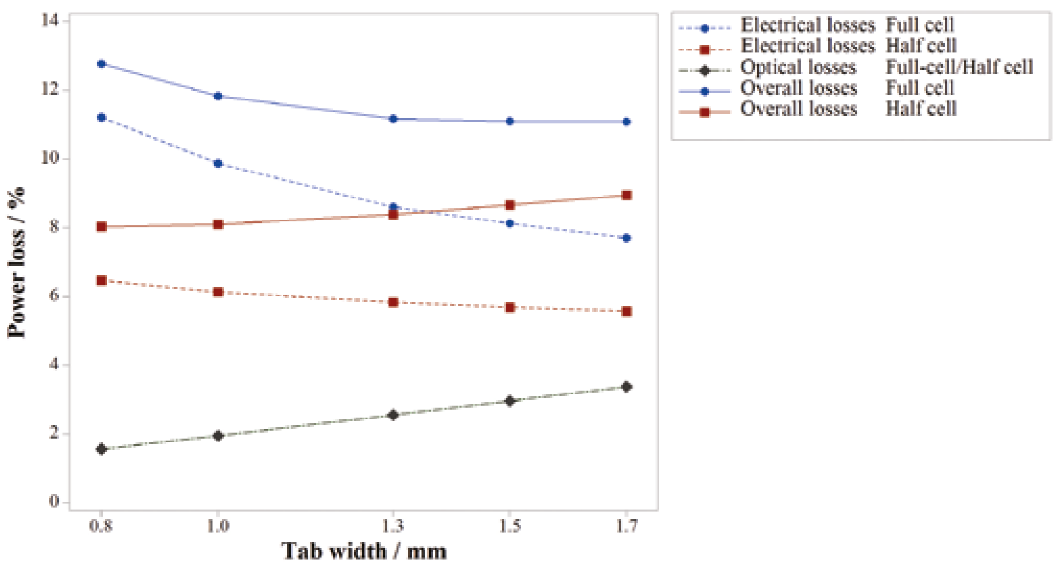

Figure 7. Optical shading, electrical and overall losses of three-busbar, full-cell and half-cell modules as a function of tab width at STC, without considering other optical gains in the module. The optical losses for both modules are the same [4].

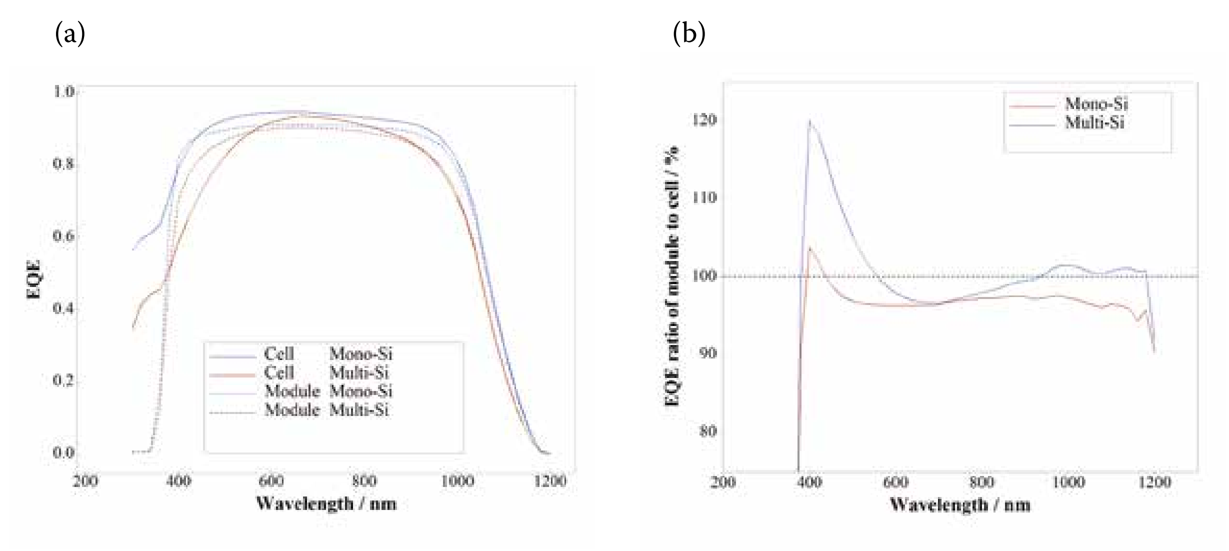

Figure 8. (a) Measured EQE for multi-Si and mono-Si solar cells and their corresponding mini-modules. (b) Measured module-to-cell EQE ratio for these two technologies.

Light-intensity-resolved CTM

Most of the efficiency evaluations of PV modules are referred to STC. It is important, however, to understand the loss mechanisms at different irradiation levels, especially low-light conditions. Fig. 9 shows the simulation results for the efficiencies of half-cell and full-cell modules described in the earlier section on interconnection electrical loss reduction, with two optimized tab widths and at different irradiation levels.

At high irradiation levels the electrical losses are the major reason for power loss in full-cell module interconnections, whereas half-cell modules demonstrate better performance at high levels because of reduced electrical current. The overall power loss trend in half-cell modules, however, indicates that the optical losses caused by the tabs are the dominant loss mechanism in full-cell modules at high irradiation levels.

In low-light conditions the optical losses are the dominant loss mechanism for both types of module [4]. Therefore, in locations with low irradiation levels, there could be a benefit of higher efficiencies with modules having narrow tab widths than with modules having wider tabs.

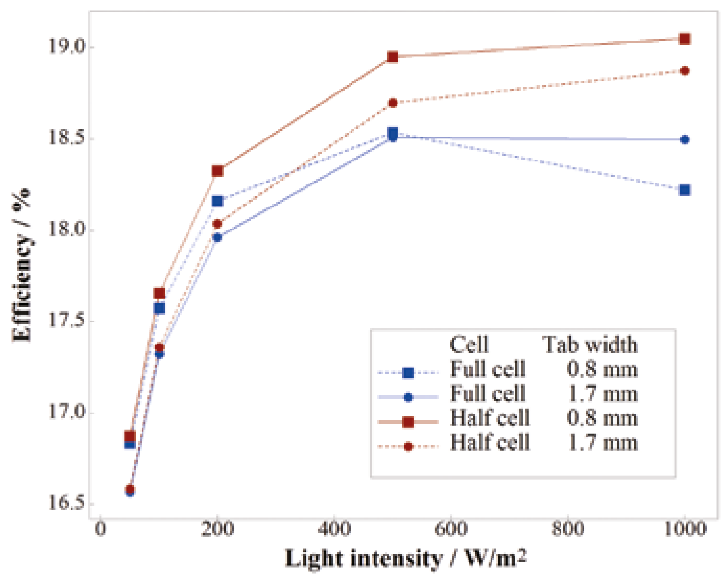

Figure 9. Efficiencies of half-cell and full-cell layouts with respect to irradiation, for two optimized tab widths. The continuous lines on the graph represent the optimized tab widths.

Energy yield in different locations

As mentioned in the previous section, the loss mechanisms at various irradiation levels are different for full-cell modules. This explains the need to consider energy yield calculations when determining the best module design for different locations in order to increase the CTM ratio.

Fig. 10(a) demonstrates the periods (average hours per year) of different irradiance levels determined for a moderate climate (Germany) and a desert climate (Morocco). The data used were accumulated between 2012 and 2014, without considering the night time. The results demonstrate the more frequent occurrence of high-level irradiation in a desert climate than in a moderate climate, which leads to higher electrical losses in module interconnections [4].

The simulation results of the energy yield based on the overall loss results for the modules mentioned in the section on interconnection electrical loss reduction are shown in Fig. 10(b) [4]. These results confirm that the energy yield of half-cell modules is consistently higher than that of a full-cell layout, because of the reduced electrical losses. Furthermore, the changes between electrical and optical losses at different irradiation levels cause the optimum tab width for a full-cell module to shift to 1.3mm from the 1.7mm already simulated for STC. In this case, compared with full-cell modules the half-cell modules benefit from a greater energy yield of 1.52% and 2.20% for the moderate (Germany) and desert (Morocco) regions respectively [4]. It can be deduced that it is not sufficient to consider just STC when

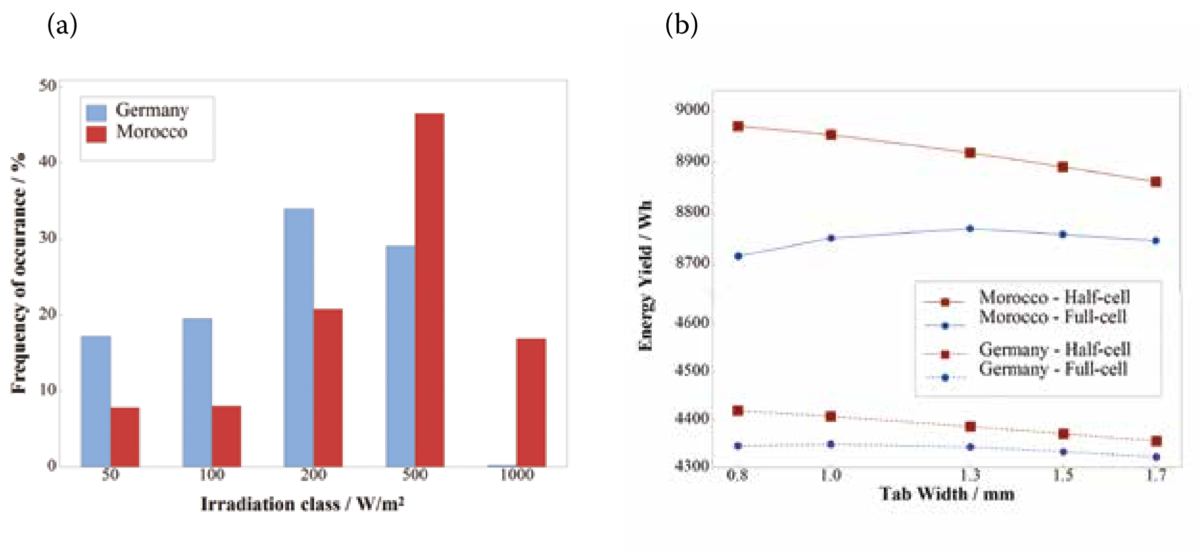

Figure 10. (a) Relative frequency of average annual irradiation over three years, along with the corresponding irradiation levels, in Morocco and Germany for 2012 to 2014; (b) related energy yield calculations for the half-cell and full-cell mini-modules using different tab widths [4].

analysing the losses. Energy yield analysis is a tool that can be used to quantify the module behaviour under different environmental conditions in order to propose better module designs.

Conclusions and future work

In the work presented in this paper, the different loss and gain mechanisms in PV modules were reviewed. It was also shown that with the use of novel module designs, it is possible to minimize the losses and increase the gains. The conclusions can be summarized as follows:

- The interaction of individual layers and components is important.
- By modifying module integrations – such as glass thickness, backsheet or tabs – the optical losses and gains can be optimized.
- Modules with cut cells demonstrate better CTM ratios because of lower electrical losses and higher optical gains.
- Cutting solar cells leads to a slight decrease in cell efficiency, but this loss is offset at the module level.
- The efficiency of half-cell modules can be increased by using a narrower tab width.
- The cell type and sensitivity are important. For solar cells with lower efficiency (multi-Si) due to the different reflectance of the cell surfaces and direct coupling gain, a higher relative CTM gain than for high-efficiency mono-Si cells is achievable.
- A better UV and near-IR response makes multi-Si cells more suitable for extreme climates, such as in highlands and deserts.
- The dominant loss mechanisms for tabs vary with different irradiation levels. Electrical losses are the dominant power loss mechanism for full-cell modules at high-irradiation levels, while optical losses are behind the main power loss in low-light conditions. In the case of half-cell modules, optical losses are the major cause of power loss in both irradiation conditions.
- Referencing only to STC is not adequate when looking to optimize module design for different locations. Energy yield analysis is a good tool to use for designing modules with higher CTM ratios at different environmental conditions.
- The results show that with the use of novel module technology techniques, it is possible to obtain higher CTM ratios and achieve economic benefits over optimized module integrations.

The optical characterizations presented here were carried out for light with a perpendicular angle of incidence. In order to qualify the behaviour of PV modules under irradiation at different angles of incidence and in different locations, energy yield measurements are also recommended.

"With the use of novel module technology techniques, it is possible to obtain higher CTM ratios and achieve economic benefits over optimized module integrations."

In this paper the investigation of the response of standard mono- and multicrystalline solar cells was presented; the behaviour of other cell concepts – such as bifacial and PERC cells or other cell designs (e.g. cells with more than three busbars or multi-wire technologies) – is proposed for future studies.

Besides the effect of module integrations on CTM ratios, the role that the electrical interconnection and novel module designs can play on loss and gain mechanisms in PV modules is another consideration. A half-cell layout has been compared with a layout incorporating standard-size solar cells, but other designs – such as one-third or one-quarter cell layouts – should be investigated.

Finally, the yield of solar modules in non-STC conditions (such as in deserts) by taking into account the irradiation was discussed. However, other environmental conditions, such as temperature, also need to be considered.

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