

5th Workshop on Metallization for Crystalline Silicon Solar Cells

The effect of reduced silver paste consumption on the cost per Wp for tab-based modules and conductive-foil based modules.

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Currently Ag-paste consumption the most important cost factor for cell processing. Cell manufacturers are putting a great deal of effort into the reduction of Ag-paste usage. This leads to higher line resistances of the Ag-paste fingers and results in a trend in the photovoltaic market to apply more busbars per cell. More busbars mean more tabs in the module causing less resistive losses on module-level. In this work we perform cost-per-Wp computations using a model that treats cells and module in an integral way, based on analytical calculations. We show that the cost-per-Wp of tab-based modules can be reduced by applying lower and/or narrower Ag-paste fingers. We compare the reduced cost-per-Wp values of a tab-based module to an innovative conductive foil-based module. We show that the conductive foil-based module has a lower cost-per-Wp despite the extra cost of the foil. Furthermore, the use of lower and/or narrower fingers results in a further reduction of the cost-per-Wp values for the foil-based module as well.

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1. Introduction

Currently the cost of photovoltaic modules, composed of mc-Si solar cells, can be broken down into a share of 56% for the cells and 44% for the module. The 56% of the cell cost can be broken down into 32% for the material (from poly-silicon to wafers) and 23% for cell processing [1]. The dominant cost factor of the latter is the use of screen printable silver paste. The silver paste is used as metallization of the front grid with typical metal coverages of 4-7% percent. The commonly applied pattern is referred to as H-pattern, consisting of broad leads, the so-called busbars, and perpendicularly to that very fine leads, the so-called fingers. Metal strips, called ribbons or tabs, are used to make the series interconnection from one cell to its neighboring cell. These tabs are soldered on the front side busbars and soldered on silver pads on the rear side of the neighboring cell. Since the cell processing cost is dominated by the use of Ag-paste, cell manufacturers focus on the reduction of Ag-paste usage. Due to

technological advancements cell manufacturers and suppliers of screen or stencil print equipment manage to print Ag-fingers that are narrower and with a reduced height. As a consequence of this the line resistance in Ω/cm of the fingers increases. The associated Ohmic losses in the metal fingers can be kept at acceptable levels by applying more busbars and correspondingly more tabs. Nowadays, a trend in the PV market can be observed where module manufacturers are moving from two tabs per cell to modules with three to five tabs per cell.

An alternative to a tab-based module is the foil-based module. This innovative module contains an electrically conductive foil that is patterned such that it has areas that contact the p-type contacts of one cell and the n-type contacts of the neighboring cell, thereby establishing a series connection.

Foil-based modules are well-known because of their low resistive losses in the module interconnection material in comparison with tabbed modules [2]. However, due to the trend of the increasing number of busbars/tabs per cell for the tabbed modules, the advantage of the foil-based module might be strongly reduced. This work assesses the performance of both tabbed modules and foil-based modules in scenarios where the Ag-paste usage is reduced. An optimization study, based on computer simulations, has been carried out where both module types have been minimized for cost [€] per Watt-peak.

Nomenclature

MWT	Metal Wrap Through
BC	Back contacted
mc-Si	multi crystalline silicon
PV	photovoltaic
Wp	Watt-peak
BSF	Back Surface Field
ECA	Electrically Conductive Adhesive

2. Optimization study

In this work we present the results of a simulation study in which we have modelled both a conventional tab-based module that contains standard p-type H-pattern cells and an innovative module based on electrically conductive foil with MWT cells mounted on it. Our aim is to ‘optimize’ both types of modules and compare them. Here, we put the term “optimize” in between quotes since its use is improper¹. Our objective is to minimize the cost-per-Wp on module level.

In the simulations we vary the configuration of cells (metallization) and corresponding interconnection on module level. The main parameter that is considered is the line resistance of the screen printed front Ag-paste lines, since this is the dominant parameter for both cost and performance. First, we discuss the configuration of the modules under consideration and then we explain the model that has been used.

¹ The term “optimize” is according to the author often improperly used. People tend to use this term when they mean “maximize” or “minimize” one or another quantity. The term optimize can only refer to the best choice when two or more incomparable quantities are weighed. For example, the optimal car to be purchased can depend on its fuel consumption, its acceleration, its cost price and its maximum speed. What is optimal in this case depends on the buyer and will be rather subjective. A way to quantify this, can be done by introducing a ‘cost function’ that contains all quantities and where all quantities are weighed by weight parameter. The optimization can then be translated into a function minimization. If one deals with only one quantity the term ‘optimization’ should thus be avoided and should be replaced by either minimization or maximization.

2.1. Module types

We consider two types of modules: The tab-based module and the foil-based module (see Figure 1). The tabbed module is the conventional module that currently dominates the market. In this study we consider a tabbed module that contains 60 p-type solar cells with on their front sides screen-printed Ag-paste in an H-pattern metallization grid and on their rear sides full-area Al BSF. Each busbar of the front-side H-pattern grid is accompanied by screen printed Ag-pads on the rear side. The amount of silver paste used on the rear side is assumed to be 17 mg per busbar, which is based on industry information. In this study, we furthermore assume that every busbar has ten solder joints and that the busbars are linearly tapered towards the solder joints. This is not yet broadly applied by the industry but is based on the envisaged reduced Ag paste consumption in the nearby future.

The foil-based module contains p-type MWT cells that differ from the conventional solar cells in that they have a number of vias through which the front Ag metallization is brought to the rear side. The pattern topology is exactly the same as for the tabbed modules, i.e. tapered busbars and fingers perpendicularly to that. The difference is that in each basis of the tapered busbar a via is present in which metallization is wrapped through to the rear side.

The vias, made by laser ‘drilling’, typically have diameters of 200 μm and each via is filled with Ag paste and accompanied by a circular Ag pad on the rear side of the cell. These pads are connected through the vias to the front side metallization grid that contacts the emitter. Therefore these pads are referred to as the emitter contacts. On the rear side also base contact pads are present that are connected with the Al rear side.

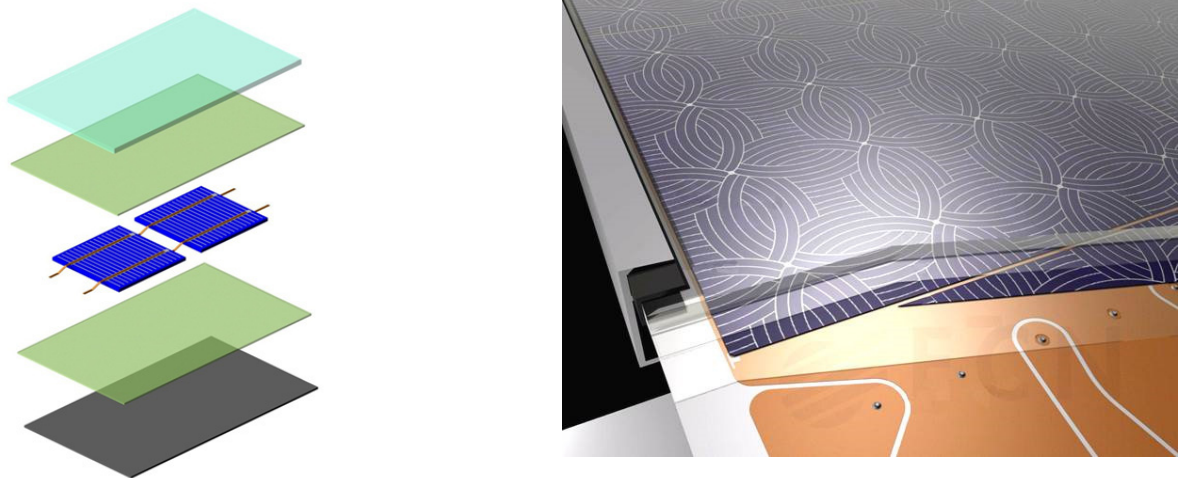


Figure 1 Left: lay-up of a conventional tab-based module. Right: Lay-out of foil-based module, where the copper foil is patterned. The connection between the cells and the foil is made with ECA dots. These dots cure during lamination of the module. Between the copper foil and the solar cell a punched sheet of EVA is present. The metallization pattern of the cells is model registered by ECN (patent pending 001748476-0001).

In a conductive foil based module [2] the MWT cells are connected to the patterned electrically conductive foil by ECA. Here, the pattern in the foil is such that the emitter contacts of one cell are connected to the base contacts of the neighboring cell. The foil pattern contains interdigitated ‘foil-fingers’, where adjacent foil fingers are contacting base and emitter contacts in an alternating sense. Each foil-finger is tapered thereby realizing an efficient way of current transport. The copper foil used in these modules has a thickness of 35 μm . The patterns on the short edges of the module differs from those underneath the majority of the cells, since the current has to make a ‘bend’ in this area. The associated ‘corner foil’ patterns are less than twice as resistant as the ‘straight’ foil patterns. The effective resistance of the foil, averaged over the different pattern types is typically only 0.18 $\Omega \text{ cm}^2$. This is very low compared to the equivalent resistance of a tabbed module with three tabs per cell (1.5 mm broad, 200 μm high)

that amounts to $0.47 \Omega \text{cm}^2$. By dividing these numbers with the characteristic resistances of the (encapsulated) solar cell, defined by $R_{\text{ch}} = V_{\text{oc}}/J_{\text{sc}}$ one simply obtains the relative fill factor decrease (eq. 5.17 [3]) associated with the interconnection losses.

Applying typical mc-Si solar cell numbers of $V_{\text{oc}} = 0.630 \text{ V}$ and $J_{\text{sc}} = 36.5 \text{ mA cm}^{-2}$ one obtains a characteristic cell resistance of $17.3 \Omega \text{cm}^2$. Hence, the mentioned interconnection resistance results in a relative fill factor drop of $0.18/17.3 \approx 1.0\%$ for foil-based interconnection and 2.7% for three-tabs based interconnection. For the sake of simplicity, we omitted in this example, for foil-based modules, the resistances of the ECA connections and, for the tabbed modules, the resistance of the solder joints as well as that of the bussing. This example illustrates the advantage of foil-based modules compared with conventional tabbed modules. To first order approximation this also indicates that eight busbars per cell ($0.47 \Omega \text{cm}^2 \cdot 3 / 0.18 \Omega \text{cm}^2 \approx 8$) are required to achieve the same interconnection resistive loss level as for the conductive foil.

Due to the reduction of Ag-paste consumption, driven by cost reduction, and corresponding higher line resistances of metallization fingers, an increasing number of cell manufacturers apply more than the conventional two or three busbars per cell to keep the resistive losses at an acceptable level. Accordingly, more tabs per cell will be used and the associated interconnection losses of tabbed modules will decrease. This suggests that the interconnection related cell-to-module fill factor loss gap between foil-based modules and tab-based module is narrowing. At the same time, more tabs results in more shadow losses which poses a negative feedback on the module power. In this work we determine the optimal configuration for both types of modules for varying Ag-paste line resistances, and we compare the performance of tabbed modules with foil-based modules.

2.2. Model

We simulate a module by taking into account both cells and interconnection material. Therefore this study could be denoted as an integral optimization. As far as the solar cell is concerned we vary the metallization configuration. The metal configuration is governed by the parameters listed in Table 1.

Table 1 Parameters varied in the optimization study

notation	Item	Explanation
nof	Number of fingers	
nob	Number of busbars	
nocbb	Number of contacts per busbar	Solder joints for tab-based module and ECA dots for the foil-based module.
bbw	Busbar width [cm]	The maximum width at the basis of a tapered busbar.
fw	Finger width [cm]	
ρ_t	Line resistance [Ω/cm]	

For the tab-based module obviously the number of tabs equals the number of busbars. The six parameters of Table 1 determine both the module power and the cost of the module. The module power is determined by the metallization on the solar cell as well as by the interconnection properties. The metallization coverage on cell level determines the shadow fraction and therefore the short circuit current. For the foil-based module the area of both fingers and busbars determine the shadow fraction. For tab-based modules, however, the fingers and the tabs (which cover more area than the tapered busbars) determine the shadow fraction. For the fingers we apply an effective shadow fraction of 50%. This can be attributed to light scattering from finger and subsequent total internal reflection at the glass-air interface inside the module [6,7]. The short circuit current density, for the encapsulated cell, is simply calculated by correcting a ‘shadowless’ short circuit $J_{\text{sc},0} = 39.7 \text{ mAcm}^{-2}$ for the shadow fraction.

Metal that contacts the emitter also leads to an increased surface recombination, resulting in a lower open circuit voltage. We have taken this V_{oc} degradation into account by using an empirical model where the metal-less $V_{\text{oc},0}$ of 640 mV is reduced by 2 mV for every 1% metallization fraction based on observations in our laboratory and confirmed by fig.3 of [4]. For example, 5% metallization coverage results in a V_{oc} of 630 mV.

The fill factor loss is computed according to $FF = FF_0(1 - R_s V_{oc} / J_{sc})$ (eq. 5.17 of [3]), where the resistance R_s in Ωcm^2 is computed in an analytical way. The pseudo fill factor is given by $FF_0 = (v_{oc} - \ln(v_{oc} + 0.72)) / (v_{oc} + 1)$ (eq. 5.15 of [3]), where $v_{oc} = V_{oc} / (nk_B T / q)$ is the open-circuit voltage normalized with the thermal voltage times the non-ideality factor n that was assumed to be equal to one. The series resistance is simply an aggregation of interconnection related series resistances and series resistances on cell level. The series resistances associated with the interconnection are listed in Table 2.

Table 2 Resistances used in computations

	Tab-based module	Foil-based module
Effective resistance	1.0 mm tab: 1.06 Ωcm^2 (2 tabs)	Avg. foil resistance: 0.18 Ωcm^2
	0.71 Ωcm^2 (3 tabs)	
	0.53 Ωcm^2 (4 tabs)	
	1.5 mm tab: 0.71 Ωcm^2 (2 tabs)	
	0.47 Ωcm^2 (3 tabs)	
	0.35 Ωcm^2 (4 tabs)	
	etc.	
	Bussing resistance neglected	
Interconnection material	Solder joint resistance:	ECA contact:
	0 Ω per contact	1 m Ω per contact
Both module types		
Emitter sheet resistance	85 Ω/sq	
Specific contact resistance	3 m Ωcm^2	

The series resistance of the ECA dots is a lumped value accounting for the resistance of the bulk as well as of the contact resistance from the copper/ECA interface and the ECA/Ag-paste interface and are assumed to be 1 m Ω per dot. The total resistance per cell for the ECA dots is simply the one-dot resistance divided by the number of ECA dots. The series resistance due to the tabs in the tab-based module scales inversely with the number of tabs.

The series resistance on cell level is a summation of the series resistance due to lateral transport in the emitter, the contact resistance, resistance due to Ohmic losses in the metal fingers and the resistance due to Ohmic losses in the tapered busbars. These resistances are analytically calculated in a straight-forward way (e.g. see sect.8.6 of [3] or [5]). Assumptions for the specific contact resistance and the emitter sheet resistance are listed in Table 2.

Table 3 Cost assumptions

Both modules		
Ag-paste price 0.75 €/gr		
Default Ag usage front side: 29 mg per % coverage.		
Lumped 'base cost' module: 127 €		
	Tab-based module	Foil-based module
Metals	1 € (two tabs), 1.5€ (three tabs), 2 € (four tabs) etc. 0 € for bussing	Extra cost Cu-foil: 6 €
Contacts	Solder 0 €	Laser cost per via 0.06 €ct Ag-pad per contact 0.02 €ct ECA cost per contact 0.01 €ct
Equipment/labor/building	9 €/module	6 €/module
Ag-paste rear pads	17mg Ag-paste/busbar 1.3 €ct/busbar	

The assumptions for the cost factors are listed in Table 3. The costs are computed as follows. Both modules have a base cost of 127 €, which is a cost number that lumps all cost (wafers, processing, module materials like glass, EVA etc.) that the tab-based module and the foil-based module have in common. The cost that both modules do not have in common are listed in Table 3. These costs factors can be divided in fixed cost per module, like the equipment/labor/building cost per module and Cu-foil cost, and variable cost. The latter is determined by the usage of Ag-paste, determined by all parameters listed in Table 2, by the number of tabs and by the number of emitter contacts, for the foil-based module. The Ag-paste usage is assumed to be 29 mg for every 1% of Ag-paste coverage. This number is scaled down if we assume lower height for the screen printed Ag-fingers as will be discussed in the next section. Table 3 shows that for the emitter contacts of the foil-based module the laser cost, for shooting a hole in the wafer, is the dominant cost factor. Clearly, if this cost factor is brought down, more vias become cost effective, which implies that less Ag-paste is needed for conduction to attain an acceptable resistive loss level and hence a further cost reduction is within reach. The ECA dot cost is based on the assumption of 200 €/kg ECA and an ECA dot diameter of 1.4 mm and a height of 100 µm (after lamination).

The module power is computed by converting the cell efficiency, i.e. $J_{sc}V_{oc}FF$, to power in the straight-forward way. Light encoupling due to reflection of light from module material in between cells or from the module edges into the cells has been neglected, for both module types. The module power depends on all variables in Table 1 and therefore the module power can be written as a function of 6 variables (eq. 1).

$$P_{module}[W_p] = f(nof, nob, nocbb, bbw, fw, \rho_l) \quad (1)$$

$$Cost_{module}[€] = g(nof, nob, nocbb, bbw, fw, \rho_l) \quad (2)$$

$$Cost_{module}[€/W_p] = \frac{Cost_{module}[€]}{P_{module}[W_p]} \quad (3)$$

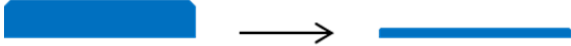
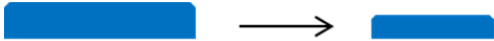
Likewise, the cost is a function of the same 6 variables as shown by eq.2. Here, the finger width fw and the line resistance ρ_l determine indirectly the Ag-paste mass. For the default finger property of $fw=70\mu m$ and $\rho_l=0.36 \Omega/cm$ the mass-to-coverage ratio is 29 mg per % metal coverage (see Table 3). For the same finger width but for higher ρ_l the mass-to-coverage ratio scales inversely proportional with ρ_l and thus the Ag-cost scales accordingly. For the tabbed module the number of busbars determines the number of tabs, which result in higher tab cost. The number of contacts (i.e. solder joints) is for the tabbed-module fixed to ten and the associated solder cost is neglected. For the foil-based module the number of contacts per busbar varies with a cap of twelve because of a technological constraints in module manufacturing. Note that the number of contacts per busbar is equal to the nr. of vias per busbar, the nr. of emitter pads per busbar and the nr. of ECA dots per busbar.

2.3. Ag-paste reduction scenarios

In this study we will determine for a varying line resistance the cell-and-module configuration that gives the lowest cost per W_p on module level. We consider two scenarios for the variation of the line resistance that are listed in Table 4.

The first scenario can relatively easily be obtained in practice by reducing the emulsion of the screens used for screen printing. In this scenario the line resistance is simply inversely proportional with the finger height. The cost of the Ag paste used for the fingers simply scales with the finger height. For the second scenario more technological advances are needed, such as a paste that is printable at a higher resolution, finer wires for the screen's mesh and a higher wire crossing density in the mesh as well as a proper emulsion height. In the constant-aspect-ratio scenario, the line resistance is inversely proportional with the finger width squared. Our default line resistance for the Ag paste used for the front grid metallization equals $0.36 \Omega/cm$ for a line width of 70 µm.

Table 4 Scenarios for varying line resistance. The default line resistance in this study is $0.36 \Omega/\text{cm}$ for a finger width of $70 \mu\text{m}$. By decreasing the finger width and/or the finger height, the line resistance is increased and the paste mass per cm finger is decreased.

Scenario			
I	Constant finger width	Line resistance is increased by lowering the finger height	
II	Constant aspect ratio	Line resistance is increased by simultaneous decrease of width and height, while maintaining the height-to-width ratio.	

3. Results

This section shows the results of the optimization study. Figure 2, Figure 4 and Figure 6 show results of the minimum cost-per-Wp study for the “constant finger width” scenario, whereas Figure 3, Figure 5 and Figure 7 show the same but then for the “constant aspect ratio” scenario. In the graphs, the optimal cases are indicated by open circles, whereas the reference cases (i.e. $\rho_l=0.36 \Omega/\text{cm}$, finger width = $70 \mu\text{m}$) are indicated by filled circles. The reference and the optimal cases are summarized in Table 5.

Table 5 Reference cases and minimum cost-per-Wp cases for tab-based modules with tabs of 1.5 mm width and 1 mm width as well as for foil-based module. Two Ag-reduction scenarios are listed, namely the constant-finger-width scenario and the constant-aspect ratio scenario.

	Reference		Constant finger width			Constant aspect ratio finger		
			Optimal			Optimal		
	Tab (1.5 mm)	Foil	1.5 mm tabs	1 mm tabs	Foil	1.5 mm tabs	1 mm tabs	Foil
Optimal ρ_1 [Ω/cm]	0.36		0.6	0.85	0.8	1.83	1.83	1.83
Optimal finger width [μm]	70		70	70	70	31	31	31
Optimal rel. finger height	100%		60%	42%	45%	44%	44%	44%
Optimal # fingers	80	80	80	80	80	124	114	109
Optimal # busbars	3	3	3	4	5	4	5	6
Optimal # contacts per busbar	10	9	10	10	10	10	10	9
Optimal busbar width [mm]	0.49	0.35	0.77	0.77	0.35	0.71	0.53	0.34
Module power [W]	265	277	263	264	275	267	269	280
Cost-per-Wp [$\text{€}/\text{Wp}$]	0.517	0.498	0.514	0.508	0.494	0.506	0.498	0.484
$\Delta\text{Cost-per-Wp}$ [$\text{€}/\text{Wp}$]			-0.3	-0.9	-0.4	-1.1	-1.9	-1.4

Figure 2 shows that the increase of the line resistance, realized by lower paste lay down (constant finger width scenario), results, not surprisingly, in a decrease in module power. The computer program evaluates a six-dimensional parameter space to continuously find the minimum cost per Wp configuration for each line resistance. As a consequence the minimum cost-per-Wp curves have a smooth appearance, whereas the saw-tooth like behaviour of the power chart can be ascribed to a combination of continuously changing variables like finger width and stepwise changes like the number of busbars and the number of fingers when the line resistance changes. These curves show a minimum indicating that a specific line resistance exists at which the cost-per-Wp is minimal. Also it is observed that the cost-per-Wp of the foil-based module is 1.5 to 2 $\text{€}/\text{Wp}$ lower than its tabbed counterpart, despite extra costs for the foil compared with tabs. The lower cost-per-Wp can be ascribed to the combination of absence of tabs (less shadow), low foil resistance, both leading to a higher Wp, and a subtle balance of cost factors (nr of contacts per busbar and Ag-paste coverage). The lower shadow fraction also becomes visible in the higher Jsc-value in Figure 6 and the lower series resistance is seen in the high fill factor in the same figure.

Figure 2 reveals that for a tab-based module a transition from three 1.5 mm tabs and 100% finger height (solid blue circle) to four 1.0 mm tabs and 42% finger height (open red circle) yields a saving of 0.9 €/Wp. For foil-based modules a saving of 0.4 €/Wp can be achieved (from solid to open green circle) by reducing the finger height to 45% of the reference value. Note that these numbers are also listed in Table 5. Figure 4 shows the corresponding cell configurations (open circles). The minimum cost-per-Wp cases require 3, 4 and 5 busbars for the 1.5mm tab, 1mm tab and foil-based module, respectively. Note that the four 1mm-busbars only give 10% less busbar shade than the three 1.5mm busbars. Furthermore, the optimal busbar widths are lower than the tabs, indicating that a better configuration might be obtained if tabs become narrower than 1mm.

Figure 3 reflects the “constant aspect-ratio” scenario and shows roughly the same cost-per-Wp difference between the tabbed modules and the foil-based module. Moreover, the cost-per-Wp decreases for all module types with increasing line resistance (i.e. narrower and lower lines), which is of course what one would expect. Unlike in the “constant finger width” scenario the number of fingers increases quite strongly with increasing line resistance, which can be ascribed to the fact that narrower fingers imply less shadow and therefore somewhat more fingers can be easily tolerated to reduce the resistive losses in the metallization (and in the emitter). Figure 3 shows that a transition from the filled blue circle ($f_w=70\text{ }\mu\text{m}$, $\rho_l=0.36\text{ }\Omega/\text{cm}$, $\#bb=3$, $bbw=0.49\text{ mm}$, $\#of=80$, tab width=1.5mm) to the open red circle ($f_w=31\text{ }\mu\text{m}$, $\rho_l=1.83\text{ }\Omega/\text{cm}$, $\#bb=5$, $bbw=0.53\text{ mm}$, $\#of=114$, tab width 1 mm) implies for the tabbed module a cost saving of 1.9 €/Wp, which represents almost 4% cost reduction. Likewise, if the foil-based module undergoes the transition from the filled green circle to the open green circle a cost reduction of 1.4 €/Wp can be obtained, which equals nearly 3%. The configuration moves from ($f_w=70\text{ }\mu\text{m}$, $\rho_l=0.36\text{ }\Omega/\text{cm}$, $\#bb=4$, $bbw=0.35\text{ mm}$, $\#of=80$) to ($f_w=31\text{ }\mu\text{m}$, $\rho_l=1.83\text{ }\Omega/\text{cm}$, $\#bb=6$, $bbw=0.34\text{ mm}$, $\#of=109$).

An important observation is that with increasing line resistance, at constant finger aspect ratio, the tabbed-modules are not closing the gap to the foil-based modules. The increase in fill-factor by roughly 1% that occurs when the optimal configuration increases by one more tab at $\rho_l \approx 1.4\text{ }\Omega/\text{cm}$ (tabs: Figure 5 and FF: Figure 7) is partly compensated by a lower J_{sc} due to somewhat more shadow (see Figure 7) and a lower number of fingers (see Figure 5) to get a good balance between resistive losses and Ag-paste cost. The foil based module seems to ‘benefit’ as much as the tabbed-modules, from the narrower and lower finger lines in terms of cost-per-Wp. In the case of the foil-based module the power does not change much (~1% increase from 0.36 to 1.83 Ω/cm) while cost is reduced by about 2% due to a lower Ag-consumption, albeit mitigated by more cost for the increasing number of contacts.

Figure 8 shows the Ag-paste consumption on front and rear side for all module types, in case of the “constant aspect ratio” case. Clearly the foil-based module has lower Ag-paste consumption which can be ascribed to more but narrower busbars, enabling less fingers and less consumption on the rear side compared to tabbed-modules.

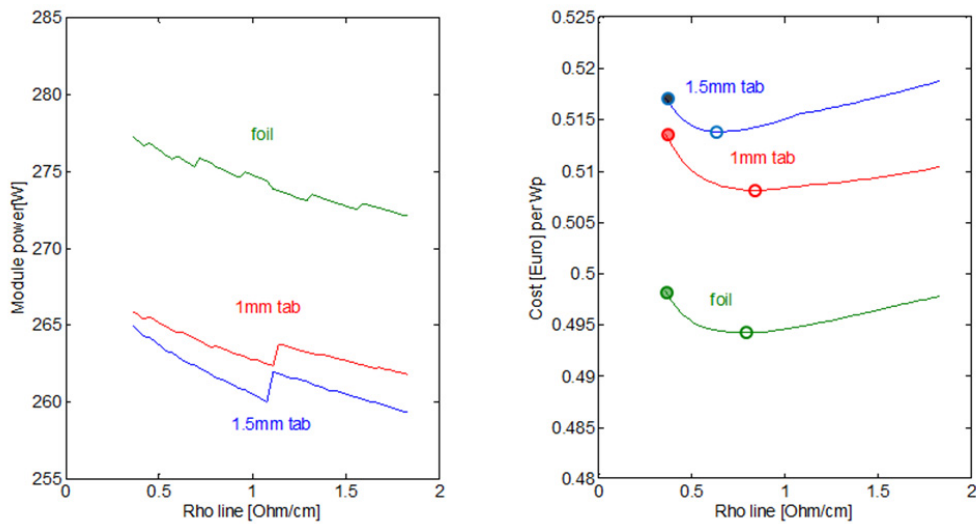


Figure 2 Results of the cost per Watt-peak minimization study, for the scenario of constant finger width. Module power (left) and cost per Wp (right). The line resistance is varied by keeping the finger width constant at $70\ \mu\text{m}$ and varying the finger height. The reference case is denoted with a filled circle, i.e. $70\ \mu\text{m}$ finger, 100% height. A minimum cost per Wp is present for $\rho_l=0.6\ \Omega/\text{cm}$ (tabs of 1.5 mm width, 60% finger height), $\rho_l=0.85\ \Omega/\text{cm}$ (tabs of 1 mm width, 42% finger height) and for $\rho_l=0.8\ \Omega/\text{cm}$ (foil-based module, 45% finger height). For a tab-based module a transition from three 1.5mm tabs, 100% finger height (solid blue circle) to four 1mm tabs, finger height 42% (open red circle) yields a saving of 0.9 €/Wp. For foil-based modules a saving of 0.4 €/Wp can be achieved (from filled to open green circle) by reducing the finger height to 45% of the reference value.

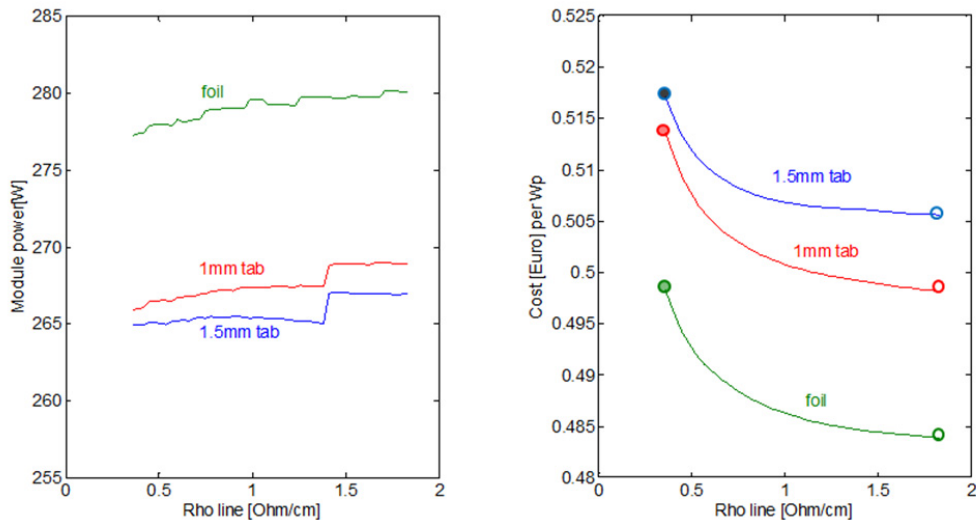


Figure 3 Results of the cost per Watt-peak minimization study, for the scenario of constant finger aspect ratio. Module power (left) and cost per Wp (right). The line resistance is increased by reducing both finger width and finger height. The reference case is denoted with the solid circle, i.e. $75\ \mu\text{m}$ finger, 100% height. The minimum cost per Wp is present for $\rho_l=1.8\ \Omega/\text{cm}$ for all module types. A reduction of 1.8 €/Wp can be achieved (from solid blue to open red circle) by reducing the finger width and height to 44% of the reference value, yielding a finger width of $31\ \mu\text{m}$. For foil-based module the reduction yields 1.4 €/Wp (from solid to open green circle).

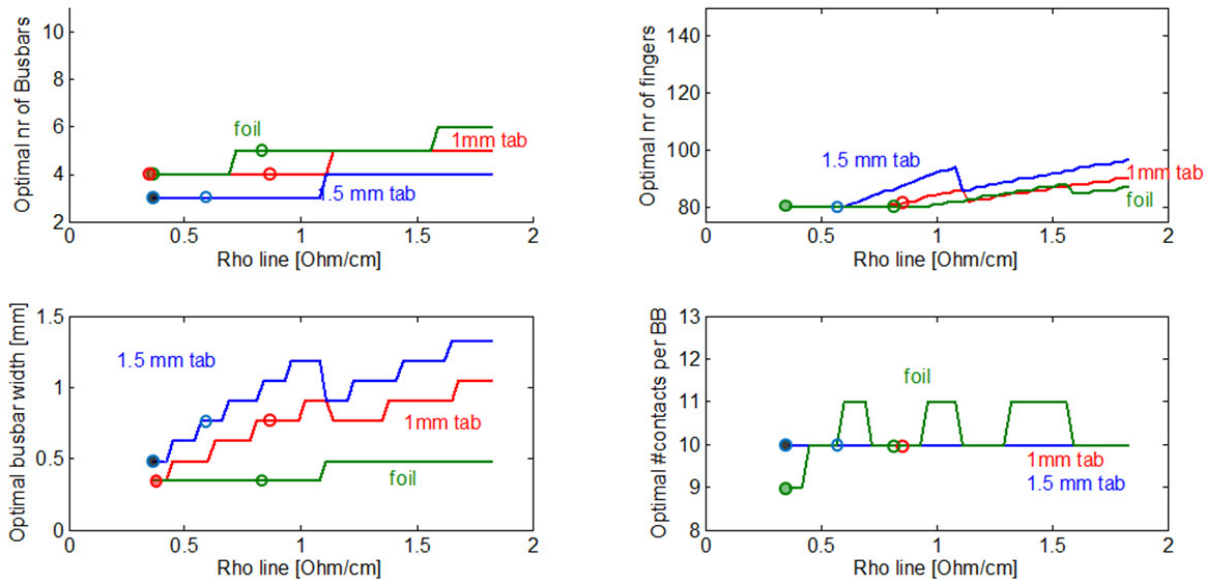


Figure 4 Optimal configuration for the cost per Watt-peak minimization study, for the scenario of constant finger width. The filled circles correspond to the reference cases and the open circles correspond to the minimal cost-per-Wp cases in Figure 2.

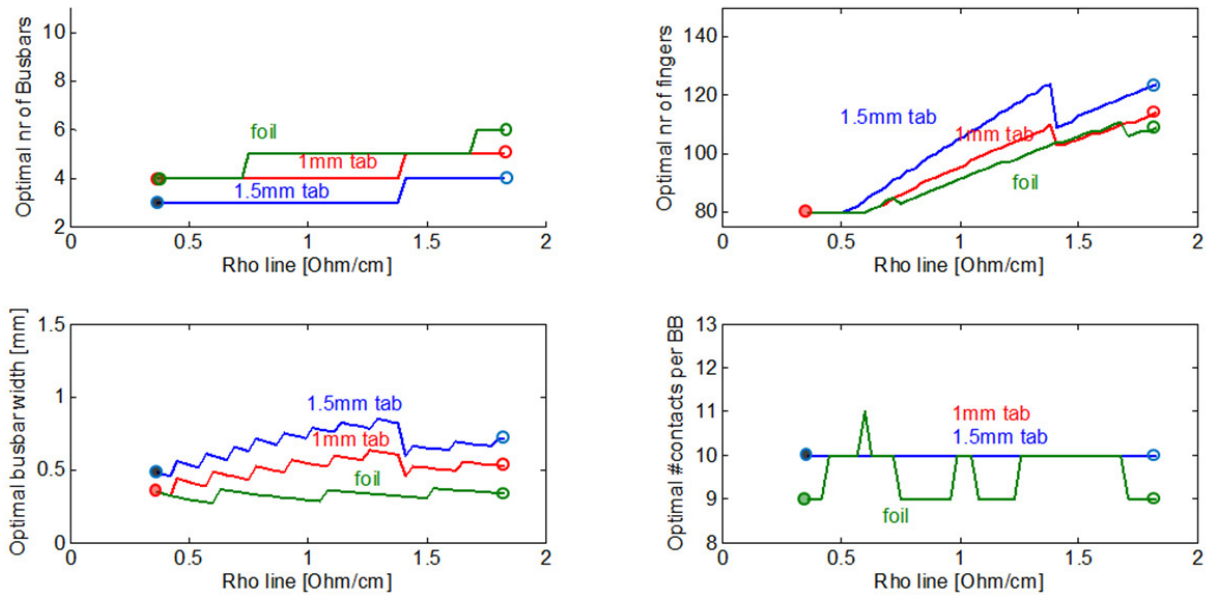


Figure 5 Optimal configuration for the cost per Watt-peak minimization study, for the scenario of constant finger aspect ratio. The filled circles correspond to the reference cases and the open circles correspond to the minimal cost-per-Wp cases in Figure 3.

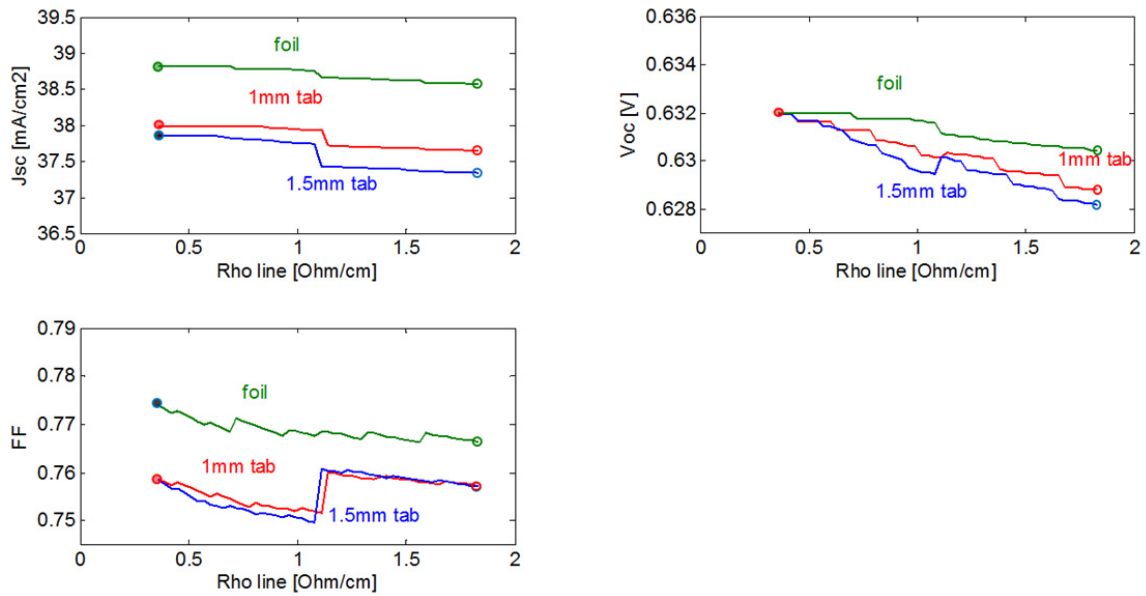


Figure 6 Cell parameters for the optimal configurations for the cost per Watt-peak minimization study, for the scenario of constant finger width. The filled circles correspond to the reference cases and the open circles correspond to the minimal cost-per-Wp cases in Figure 2 and Figure 4.

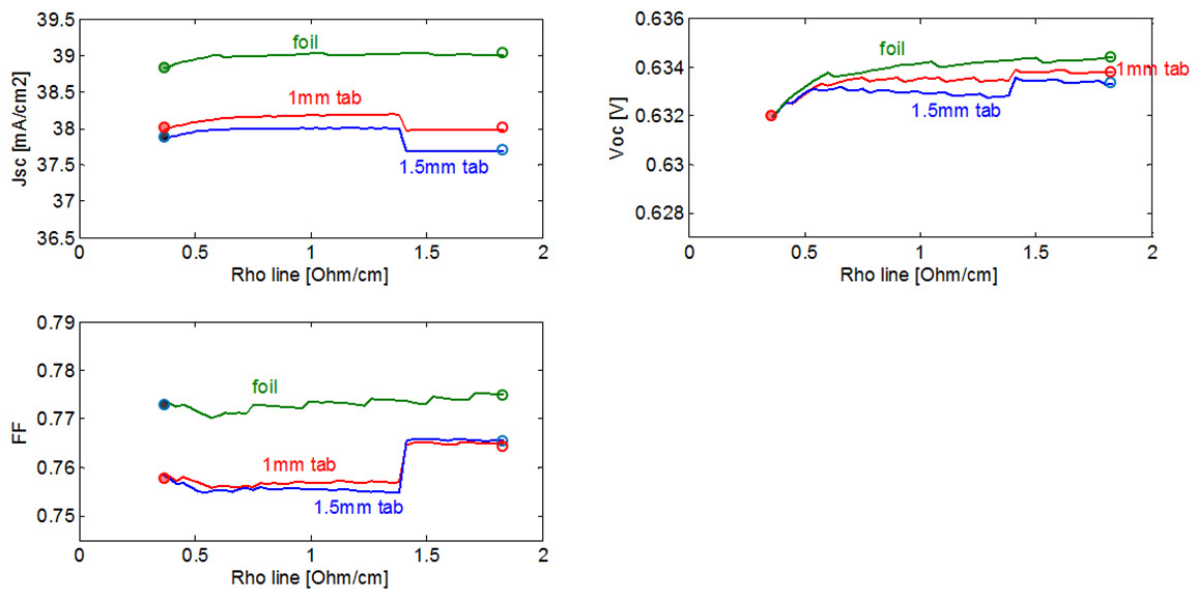


Figure 7 Cell parameters for the optimal configurations for the cost per Watt-peak minimization study, for the scenario of constant aspect ratio. The filled circles correspond to the reference cases and the open circles correspond to the minimal cost-per-Wp cases in Figure 3 and Figure 5.

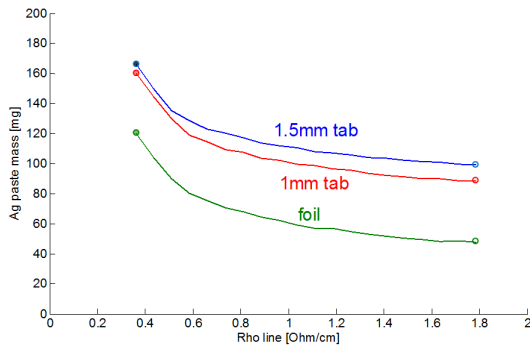


Figure 8 Ag mass usage per cell in mg for both front and rear side. Constant aspect ratio scenario.

4. Conclusion

We have presented a model that treats cells and module in an integral way. The model computes for a given finger line resistance the optimal cell configuration, which consists of the number of fingers, the number of busbars, the finger width, the busbar width and the number of contacts per busbar. We have been considering two scenarios for reducing the Ag-paste per unit length of finger: Constant finger width and constant-aspect ratio.

In the constant finger width scenario the cost-per-Wp reduction possibilities are limited: 0.4 €/ct/Wp for the foil-based module if the finger height is decreased to 45% of the reference height (line resistance $0.36 \rightarrow 0.8 \Omega/\text{cm}$). For the tabbed-module a cost reduction of 0.9 €/ct/Wp can be obtained for a configuration transition of three 1.5mm tabs to four 1mm tabs in combination with Ag-fingers with a height of 42% of the reference finger height (line resistance $0.36 \rightarrow 0.85 \Omega/\text{cm}$). The lower cost-per-Wp values are at the expense of slightly lower module powers: 0.4% (tabbed module) and 0.7% (foil based module).

For the constant aspect ratio scenario, where finger width and height scale together, higher cost-per-Wp reductions can be achieved. The tabbed module shows a cost-per-Wp reduction of 1.9 €/ct/Wp (4%) for the following configuration transition: tab width $1.5\text{mm} \rightarrow 1\text{mm}$, number of busbars $3 \rightarrow 5$, finger width $70 \rightarrow 31 \mu\text{m}$, finger height $100\% \rightarrow 44\%$ and line resistance from $0.36 \rightarrow 1.83 \Omega/\text{cm}$. The conductive foil module shows a cost-per-Wp reduction of 1.4 €/ct/Wp (3%) for the configuration transition: number of busbars $3 \rightarrow 6$, finger width $70 \rightarrow 31 \mu\text{m}$, finger height $100\% \rightarrow 44\%$ and line resistance from $0.36 \rightarrow 1.83 \Omega/\text{cm}$. In contrast to the other scenario, the constant-aspect-ratio scenario shows a cost per Wp reduction that is accompanied by a module power increase: 1.5% (tabbed module) and 1.1% (foil-based module).

To summarize, both tabbed modules and foil-based modules benefit from lower and/or narrower screen printed Ag-paste fingers. Conductive foil based modules show a 40 mg/cell lower Ag consumption and a 1.5 to 2 €/ct/Wp lower cost-per-Wp, despite the extra cost of the foil, than tabbed-modules, and, moreover, a higher power of 11 to 13 Wp.

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