OPTIMIZATION OF THE NUMBER OF BUSBARS IN CRYSTALLINE SILICON SOLAR CELLS

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Abstract. *With the growth of the photovoltaic (PV) market, the optimization of the efficiency of PV cells comes into focus; as crystalline silicon (c-Si) cell efficiencies get closer to the material's maximum theoretical efficiency, every decimal increase counts, with front metallization improvement being one of the many possible approaches. Optimizing the front metallization is a low-cost variation of the already known and merchandised PV technologies, bringing to the table the possibility of optimizing shading and resistive losses, and improving the final efficiency of the cell. In this study, c-Si PV cells were simulated with different numbers of busbars and at various irradiance levels, to obtain STC efficiency and to calculate the global efficiency for a given irradiance distribution, based on one year of one-second resolution data. The chosen location for which cells were optimized for was Brotas de Macaúbas, in Northeastern Brazil, that being a representative location for where utility-scale PV power plants are being deployed in the country. The chosen location also presents frequent over-irradiance events and overall high irradiance levels, with 31,72% of the annual energy being incident at irradiance levels above STC irradiance, for which cell efficiency is measured at. The cell efficiency simulations were carried out in the Griddler 2.5 software for a c-Si PERC M12 cell with up to 15 busbars and for irradiance levels from 0 to 1800 W/m^2. Despite the expected rise at the optimum number of busbars due to higher irradiance levels, the research concluded the optimum busbar number for STC efficiency (5BB) is still the optimum number of busbars considering the irradiance distribution of the location, despite the slight reduction in efficiency when real conditions were considered (0,48%). In conclusion, simulations showed that changing the number of busbars alone did not manage to improve the global cell efficiency for the evaluated site.*

Keywords: *Front Metallization, PV Cell Optimization, Over-irradiance.*

1. INTRODUCTION

With a closing gap between the current highest efficiencies of crystalline silicon (c-Si) photovoltaic (PV) cells – as of today, last record efficiency of 27,6% (NREL, 2021) – and the maximum theoretical efficiency of a single junction silicon cell – 32,33% (Shockley et al., 1961) – closing down, the small room for improvement results in a not-so-steep advance in c-Si cell efficiency and a fierce competition for better efficiencies. In this context, the PV c-Si cell market, has reached a limit where every fraction of energy loss reduction – and consequent efficiency increase – could mean outstanding.

Part of the energy loss of a PV cell occurs in the front metallization of the cells, which consists of busbars and fingers. This loss comes from not only from the resistance losses during conduction, but also from the shading losses of the conductors themselves. Reducing losses in the front metallization can be tricky, since both losses (shading and resistance) can be reduced by altering the number of busbars/fingers, but in opposite directions. Basically, by increasing the metallization (i.e. adding more busbars or fingers) to increase conductivity and decrease resistance losses, the shaded portion of the cell will become larger, increasing shading losses; the opposite is also true: decreasing the number of busbars or fingers would reduce shading losses, at the cost of decreasing conductivity and increasing resistance losses.

Therefore the optimization of the front metallization of a cell is, mostly, a matter of finding a balance between these two losses. Furthermore, optimizing the number of busbars and fingers would be a very cost-efficient change of layout because of the screen-printing technique.

From basic circuit theory, it is known that resistive losses increase with current, so it is expected that front metallization resistance losses are more significant for high-current PV cells and/or for high-irradiance levels, which also lead to higher currents. In this context, over-irradiance events are an important factor to be considered, especially in climates such as the one found in Brazil, where these events are frequent (Braga *et al.*, 2019) and can reach irradiance levels above 1800 W/m² (Nascimento *et al.*, 2019). Not much is known about the performance of PV cells under such high irradiance levels, with the focus of standard testing being mostly on STC and weak-light response, while hot and sunny climates could benefit from the knowledge of a PV module's "strong-light" response.

A study from Kikelj *et al.* (2020) has shown that for different irradiance levels there are different front metallization patterns necessary to achieve the optimal operation point, but literature lacks papers that evaluate the optimization of the overall performance of a PV cell operating throughout a range of real-life irradiance levels. In the present study, the authors propose a method for the optimization of front metallization of PV cells using high resolution irradiance data and the and free version of Griddler 2.5, a numerical tool which uses the finite element method. The proposed method is also applied to a case study for the optimization of the number of busbars of a M12 full-cut monofacial SE PERC silicon cell for the location of Brotas de Macaúbas, in Northeastern Brazil. Furthermore, the shading and resistance losses have been analyzed for the optimal front metallization found in the case study.

2. METHODOLOGY

In this study, the authors aim to calculate an efficiency that reflects the field operating conditions, using cell efficiency data for different irradiance levels ($\eta(G)$) and the irradiance distribution of a given site ($E(G)$). The product of these two parameters is referred to in this paper as global efficiency (η_{Global}), as described by Eq. (1). Furthermore, the research intends to optimize the number of busbars of a baseline PV cell to achieve the highest so-called global efficiency.

$$\eta_{Global} = \sum_{G=0} \eta\,(G) \cdot E(G) \tag{1}$$

The following subsections detail the methodology involved in the acquisition of the two parameters used in the calculation of the global efficiency: the irradiance distribution and the cell efficiency for various irradiance values.

2.1 Irradiance Distribution

The chosen location for the case study presented in this paper is Brotas de Macaúbas-BA (12°18' S, 42°20' W), located in Northeastern Brazil, where the Fotovoltaica-UFSC research group (www.fotovoltaica.ufsc.br) has a research and development (R&D) project site. The location was chosen for being a representative region for where utility-scale PV power plants are being deployed in the country. The chosen location also presents frequent over-irradiance events and overall high irradiance levels, as previously reported in the literature by Nascimento *et al.* (2019) and Braga *et al.* (2019).

Global latitude-tilted irradiance data was acquired with a one-second time resolution by a CMP11 pyranometer installed at the measurement station shown in Fig 1. Latitude-tilted irradiance was chosen over horizontal irradiance for better representing actual irradiance incident at ideally oriented fixed-tilt PV systems' plane of array. The analyses comprehend the period of a full year between the 1st of February 2019 and 31st of January 2020. For calculation purposes, the second-resolution irradiance data was grouped in steps of 50 W/m² using the *Pentaho Data Integration* software to obtain the amount of energy incident at different irradiance levels. Monthly and annual irradiance distribution profiles were obtained to be then used to find the optimum number of busbars for real irradiance conditions of the region.

(a) (b)

Figure 1 - R&D project site (a) and solar measurement station (b) in Brotas de Macaúbas – BA (12°18' S, 42°20' W).

2.2 Cell Simulation

For obtaining the cell efficiencies at different irradiance levels, needed indoor to calculate the global efficiency for the given site, the simulation program Griddler 2.5 was used. The software was developed in 2013 by Dr. Johnson Wong at the Solar Energy Research Institute of Singapore, and it enables a design of high functional solar cells and exposes potential improvements in their structure. Acquisition of the program can be done through the platform Griddler-Solar, which merchandises the application since 2018.

The tool allows a numerical calculation of JV curves taking into account the shape of the silicon wafer and front metallization, resistance parameters, irradiance level, among many other input variables. In this study a mono SE PERC full M12 solar cell, provided in the cell and module file library of GriddlerSolar was used as a baseline. The parameters of the cell used in the simulations can be seen on Table 1. The investigation aimed to match near future predictions of the solar market, which seems to be moving towards large area PERC cells. (ITRVP, 2021) The efficiency was obtained for variations of the baseline cell with 3 to 15 busbars at irradiance levels up to 1800 W/m² in 50 W/m² increments.

Table 1 - Main cell simulation inputs.

WAFER SHAPE AND SIZE			
Wafer type	Wafer length	Wafer width	Ingot diameter
Pseudo Square	*21 cm*	*21 cm*	*29.5 cmm*

FRONT BUSBARS		
No of busbars	Solder/Probe points	BB width
x	*20*	*0.5 mm*
Style	Busbar ending	Print Method
straight	*straight*	*Single print*

FRONT FINGERS			
No of fingers	Finger width	End joining	Edge gap
161	*30 um*	*all*	*1 mm*

FRONT METALLIZATION		
Finger sheet resistance	Finger contact resistance	Layer sheet resistance
2 mohm/sq	*2 mohm-cm²*	*127.28 ohm/sq*
Wafer internal series resistance		Internal shunt conductance
0 mohm-cm²		*1/kohm-cm²*

FRONT DIODE PARAMETERS			
1-Sun JL, non-shaded area			
41.6232 ma/cm²			
J01 passivated area	J01 metal contact	J02passivated area	J02 metal contact
35.752 fA/cm²	*546.23 fA/cm²*	*6 nA/cm²*	*20 nA/cm²*

EDGE RECOMBINATION	
J01	J02
100 fA/cm	*0 nA/cm*

3. RESULTS AND DISCUSSION

3.1 Irradiance distribution

Fig. 2 presents the overall annual irradiance distribution for the evaluated period in Brotas de Macaúbas – BA (12°18' S, 42°20' W), while Fig. 3 presents the monthly profiles. It can be observed that irradiance values ranging from 950 W/m^2 to 1050 W/m^2 contain the most energy in the yearly distribution (Fig. 2). However, Figure 3 shows that for the months of September, October, and November the energy peak happens at even higher irradiance levels, with almost 17% of the monthly energy incident at around 1050 W/m^2. The months of June and July also present a high peak (about 15%), but at a lower irradiance level, 950 W/m^2. The months of February, March and April have a more uniform irradiance distribution throughout irradiance levels, with a less prominent energy peak, but it can still be observed that a great fraction of the yearly energy is contained at irradiance levels above 1000 W/m^2.

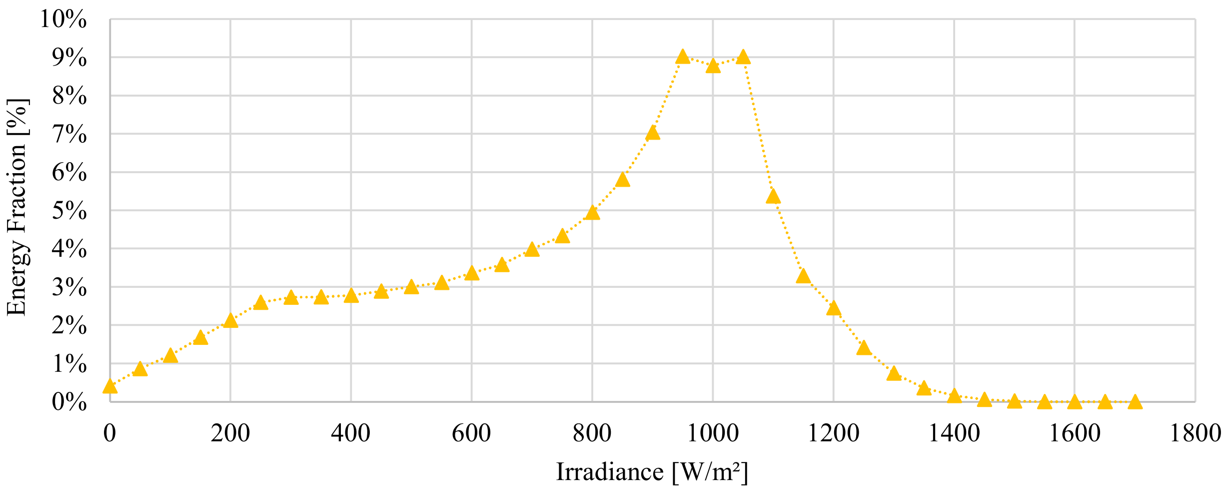

Figure 2 - Annual irradiance distribution for the evaluated period in Brotas de Macaúbas – BA (12°18' S, 42°20' W).

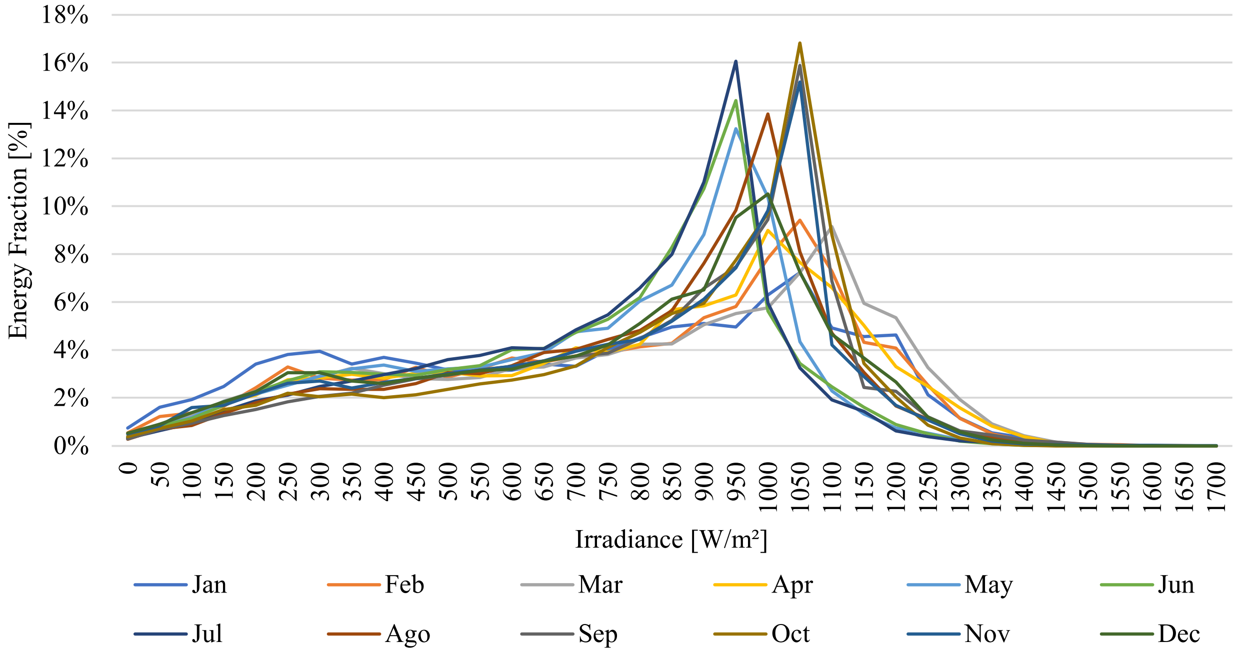

Figure 3 - Monthly irradiance distribution for the evaluated period in Brotas de Macaúbas – BA (12°18' S, 42°20' W).

Tab. 2 summarizes the irradiance distribution results by dividing the total annual energy into seven irradiance level ranges. It can be observed that over 30% (31,72%) of the total yearly energy incident at this site occurs at irradiance levels at or above 1000 W/m², a result that corroborates the previous findings of Nascimento *et al.* (2019). For energy incident at such high irradiance levels, the efficiency of the PV cell is not given by the manufacturer, and it is a fact that is not explored in the efficiency optimization process.

Table 2 - Irradiance distribution for the evaluated period in Brotas de Macaúbas – BA (12°18' S, 42°20' W).

Irradiance Level [W/m²]	Energy [%]
$0 \leq G < 250$	6,31%
$250 \leq G < 500$	13,74%
$500 \leq G < 750$	17,06%
$750 \leq G < 1000$	31,17%
$1000 \leq G < 1250$	28,94%
$1250 \leq G < 1500$	2,75%
$1500 \leq G$	0,03%

It is important to highlight that the irradiance distribution results presented in this paper are based on one-second resolution data, which are rarely found, but do better represent actual field conditions, especially for sites with frequent over-irradiance events such as the one used in this study. When using low time resolution data, irradiance peaks are smoothed out on minute or hourly averages, hiding an important fraction of energy that is incident at higher irradiance levels. This concealed problem can result in lower-than-real inverter overload losses, as approached by Nascimento *et al.* (2019), but it can also mask be a key opportunity to further optimize cell overall efficiency for high-irradiance environments. Additionally, the irradiance distribution analyses presented in this paper are based on fixed-tilt PV systems, but when considering one-axis tracker systems, which already represent nearly 100% of the new utility-scale PV plants of Brazil, it is expected that the irradiance distribution curve shifts even more towards higher irradiance levels, with even more energy concentrated at the above-STC irradiance range.

3.2 Cell Simulation

For the baseline cell selected and described in the previous section, simulation results show an optimal efficiency of 22.20% at STC for a 5-busbar configuration, as Fig. 4 shows. This matches previous results, as shown in Q. Ali *et. al.* (2019). At the irradiance level of 1000 W/m², while the shading losses account for 3,41%, the resistance losses in the front metal account only for 2,39 %.

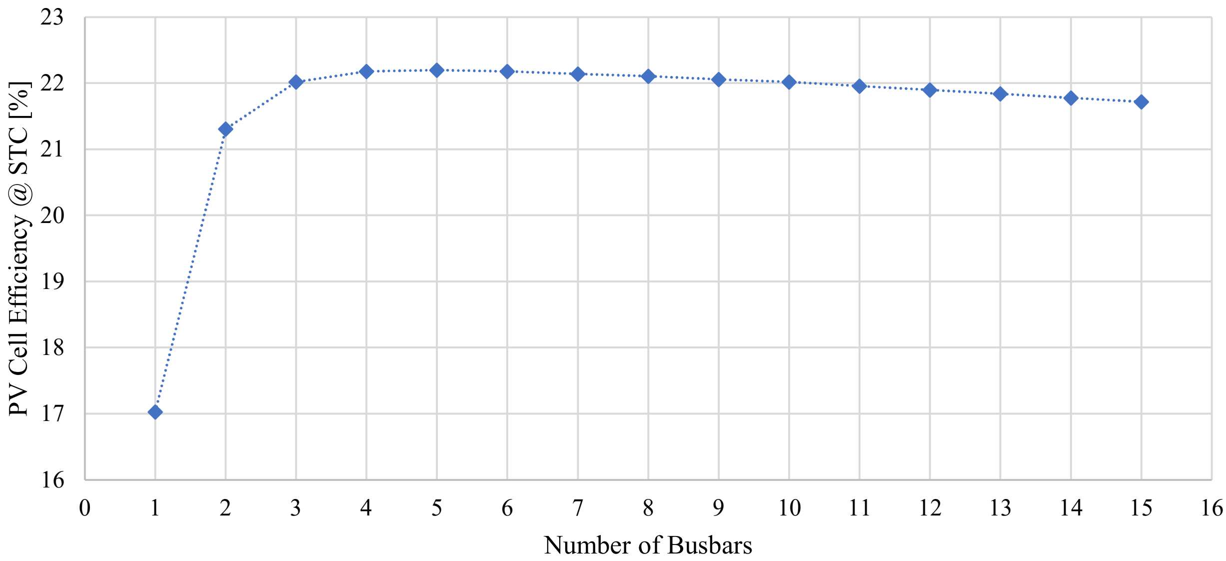

Figure 4 - Simulated PV cell efficiencies according to number of busbars for the selected baseline cell under STC.

As shown previously, due to higher overall irradiance levels, almost one third of the incident radiation in Brotas de Macaúbas-BA happens at irradiance levels at or above 1000 W/m² (Tab. 2). By variating the number of busbars in the solar cell and thus the metal covered front area, the simulation showed an optimized efficiency rate with rising busbar number in higher irradiance levels. Fig. 5 presents simulated cell efficiencies according to irradiance level for different busbar numbers, as well as the irradiance distribution for the evaluated site, for comparison. In Brazilian field conditions high irradiance levels and over-irradiance occurrences have a major impact on the performance of PV plants (Nascimento *et al.* 2019) and should also impact the selection of busbar numbers.

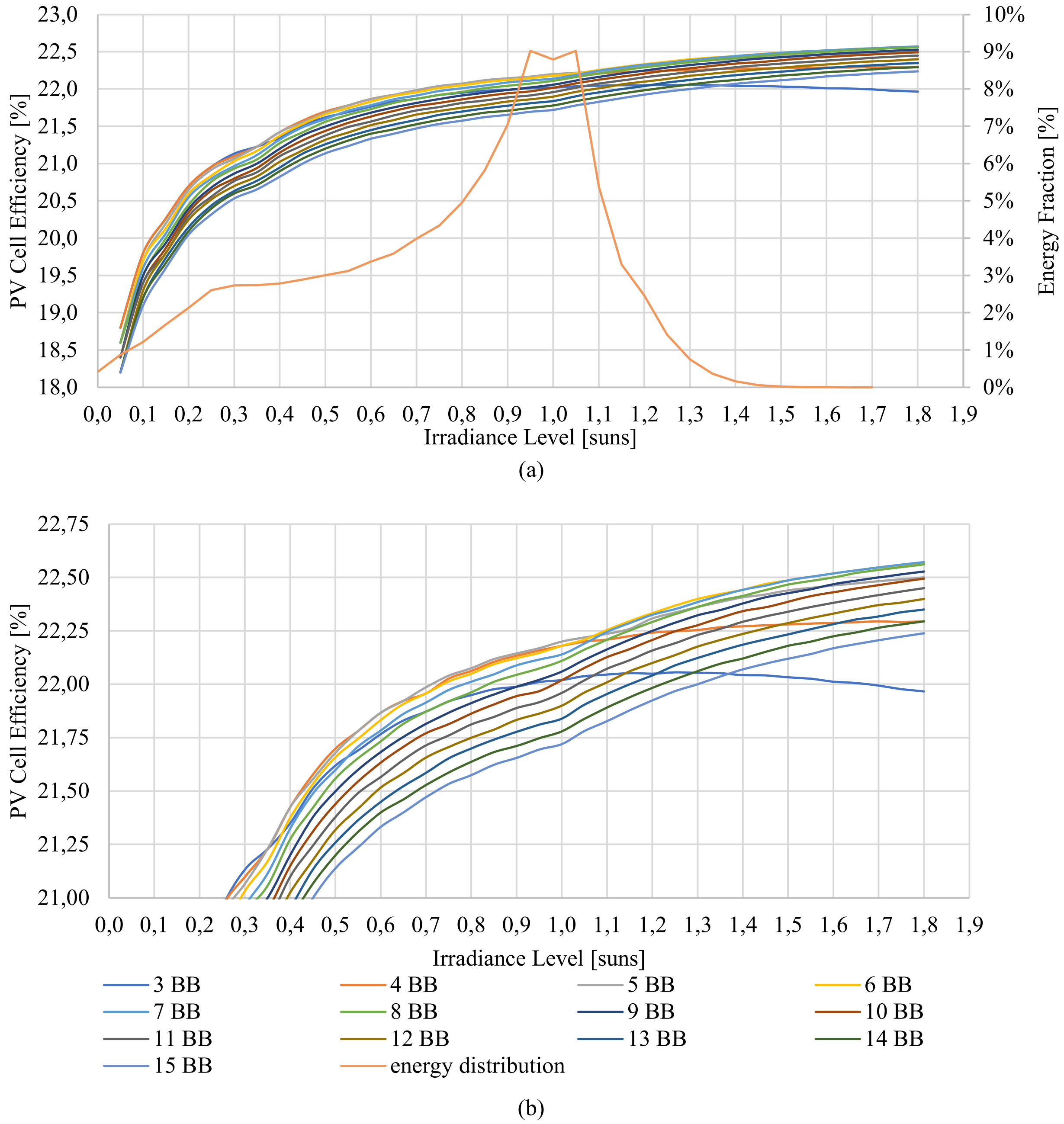

Figure 5 - (a) Efficiency of solar cells with different busbars numbers in the simulated irradiance range, (b) enlarged perspective of the previous graph.

For lower irradiance levels, a lower number of busbars is more optimal rather than higher and vice versa, due to the tradeoff between shading and resistive losses, and the impact of current on the latter. All efficiency curves resemble e-functions until their peak point, which rises equally per busbar. After the maximum point, the efficiency decreases constantly. A full trend can be observed for 3 BB in Fig. 5. For all busbar configurations above 5BB, the efficiency curve does not reach its maximum in the analyzed interval (up to 1.8 suns).

Near certain irradiance levels Fig. 5 shows a change of voltage at the maximum power point, namely: 150 W/m², from 525 mV to 550 mV; 350 W/m² from 550 mV to 575 mV; and 1000 W/m² from 575 mV to 600 mV. The nature of this variations seems to be related to limitations on the voltage step of the software's simulation of the JV curve, resulting in a slight variation on the shape of the efficiency curve at these irradiance levels.

Fig. 6 presents the global efficiency results obtained by applying Eq. (1) to the cell efficiency and irradiance distribution curves presented in Fig.5. The results show that the optimal number of busbars – considering the measured irradiance distribution of the evaluated site – is 5 BB, with a global efficiency of 21,78%. Despite the initial thesis that for locations with high irradiance levels the optimal global efficiency would come from a higher number of busbars, this result is the same as the one shown in Fig. 4 for STC conditions. Therefore, for the evaluated location a higher number of busbars and the decrease of resistance losses does not compensate the increase in shading losses, due to the higher metallization shaded area.

The efficiency for the 5BB at STC (22,20%, Fig. 4), however, differs from the one calculated through the global method (21,78%, Fig. 5), showing that the cell configuration has a slightly lower efficiency (0,48%) when the real irradiance conditions of this site are considered. This result can be traced back to higher resistive losses in the front metallization for higher irradiance/current values – a thesis corroborated by the simulations' stratified losses results, which show that the 2,39% resistive loss at STC rises up to 3,38% at 1800 W/m^2, an increase of 43%.

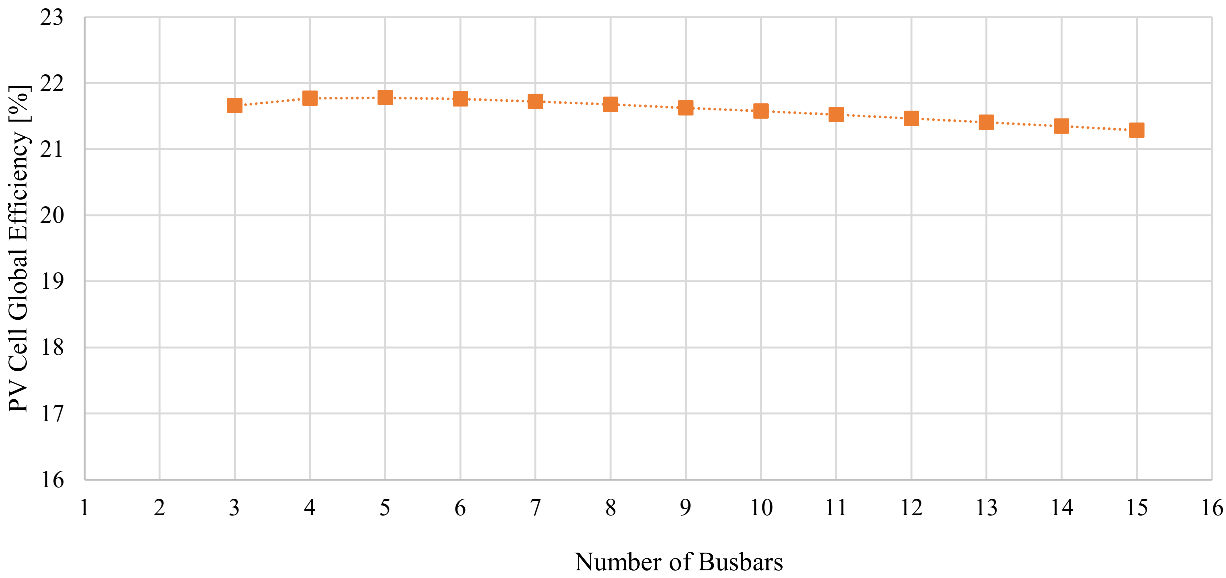

Figure 6 - Global efficiency of solar cells with different busbar numbers.

4. CONCLUSIONS

The investigation showed that there is unexplored potential in cell optimization for high irradiances in sunny climates such as the one found in Brazil. High-resolution data for the evaluated site showed almost one third of the incident energy happens at or above STC irradiance of 1000 W/m^2, with most of the annual energy contained in the range from 950 W/m^2 to 1050 W/m^2 (27%). Not much is known about the performance of PV cells under such high irradiance levels, with the focus of industry standard testing being mostly on STC and weak-light response.

Despite the thesis that the optimal number of busbars when considered a high-irradiance shifted distribution would be greater than the optimal number of busbars at STC, the results of this case study for a location in Northeastern Brazil resulted in the same optimal number of busbars in both scenarios. However, results did show higher resistive losses for higher irradiances, and a shift in efficiency when comparing STC and global efficiencies, with the latter being 0,48% lower than the former for the evaluated data.

The results presented open doors to posterior research on front metallization and general cell design optimization, for hot and sunny climates and operation conditions that differs from STC. In future studies, the authors intend to further explore this subject by evaluating the optimization of other cell parameters, such as the size, shape and number of the fingers, the front metallization material and contact resistances. The effects of temperature, which were not approached in this paper, must also be taken into account in future analyses. There parameters shall be investigated individually and combined, aiming at optimizing the global efficiency for high-irradiance locations.

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OTIMIZAÇÃO DO NÚMERO DE BUSBARS EM CÉLULAS SOLARES DE SILÍCIO CRISTALINO

Resumo. *Com o crescimento do mercado fotovoltaico (FV), a otimização das células FV entra em foco, assim que a eficiência das células de silício se aproxima da eficiência máxima teórica do material, cada décimo de aumento conta, sendo o aprimoramento da metalização frontal uma das muitas possíveis abordagens. Otimizar a metalização frontal é uma variação de baixo custo das tecnologias FV já conhecidas e comercializadas, trazendo a possibilidade de reduzir perdas por sombreamento ou resistência, e aprimorando a eficiência final da célula. Nesse estudo, Células FV c-Si foram simuladas com diferentes números de busbars e em vários níveis de irradiância, a fim de obter a eficiência das condições padrão de teste (STC, Standard Test Conditions) e calcular a eficiência global para uma dada distribuição de irradiância, baseada em um ano de dados de resolução de 1 segundo. A localização para a qual as células foram otimizadas para operar foi Brotas de Macaúbas, no nordeste do Brasil, essa sendo uma localização representativa para onde usinas fotovoltaicas de larga escala estão sendo implantadas no país. A localização escolhida também apresenta eventos de sobreirradiancia frequentes e altos níveis de irradiância em geral, com 31,72% da energia anual sendo incidente em níveis de irradiância acima da STC, para qual a eficiência das células é medida. As simulações da eficiência da célula foram feitas por meio do software Griddler 2.5 para uma célula c-Si PERC M12 com até 15 busbars e para níveis de irradiância variando de 0 até 1800 W/m^2. Apesar da expectativa de aumento no número ótimo de busbars devido aos altos níveis de irradiância, a pesquisa concluiu que o número ótimo de busbars para eficiência STC (5BB) ainda é o número ótimo de busbars considerando a distribuição de irradiância da localização, apesar da pequena redução de eficiência quando condições reais foram consideradas (0,48%). Em conclusão, as simulações mostraram que mudar somente o número de busbars não conseguiu aumentar a eficiência global da célula para a localização escolhida.*

Palavras-Chave: *Metalização Frontal, Otimização Célula FV, Sobreirradiancia.*