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FINE-TUNING OF MULTI-JUNCTION SOLAR CELLS: A THEORETICAL ASSESSMENT

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Abstract

The typical number of subcells comprised in multijunction solar cells steadily increased over the last 25 years to achieve higher electrical efficiencies. However, these cells typically show increased sensitivity to the spectral content of sunlight, and the efficiency under real conditions can be significantly affected. This study investigates whether or not fine-tuning of MJ solar cells could lead to significant improvement in the energy yield of CPV systems comprising a high number of subcells. The average incident spectrum in several cities is obtained with SMARTS, using as an input the main atmospheric parameters from AERONET database. The optimal combinations of bandgaps for all the selected locations and cell architectures comprising up to 10 subcells was derived. In particular, the improvement in the energy output achieved when using fine-tuned MJ solar cells to a mean annual spectrum in a located area is investigated. Implications for future generations for multi-junction solar cells are also discussed.

Keywords: *Multi-junction solar cells, spectral distribution, fine-tuning, energy yield, optimization,*

1. Introduction

Multi-junction solar cells could potentially achieve ultra-high solar-to-electricity conversion efficiency (Pérez-Higueras and Fernández, 2015) and are seen as one of the most promising options toward affordable solar electricity. Cells comprising up to 5 different subcells have been reported in the litterature with efficiencies currently approaching 50%. Today, the world record is held by a quadruple-junction solar cell with a conversion efficiency of 46% under concentrated sunlight (Green et al., 2015).

Increasing the number of *pn* junctions with appropriate band gaps leads to a more efficient utilization of the solar spectrum and consequently better conversion efficiencies. Nonetheless, the spectral distribution of the light reaching the cells may affect dramatically the ability of MJ cells to efficiently convert sunlight into electricity. The photovoltaic conversion efficiency is usually provided assuming a spectral distribution of the incoming light described by the AM1.5 reference spectrum. However, the spectral distribution of light is likely to vary significantly due to changes in the atmospheric parameters, and the ability of MJ cells comprising a high number of subcells to accommodate changes in the spectral distribution was recently questioned (Chan et al., 2014; Vossier et al., 2015). In particular, the energy output of CPV systems was shown to be highly dependent on the climatic conditions to which it is exposed. Fine-tuning of solar cells is often mentioned as a promising strategy toward increasing the efficiency with which solar energy is converted into electricity: Fine-tuning basically consists in tailoring the combination of electronic gaps comprised in the MJ stack to the spectral distribution characteristic of a particular location. This raises the question of whether or not CPV systems involving fined-tuned MJ solar cells are likely to outperform conventional MJ cells designed according to the AM1.5D reference solar spectrum, taking into account the typical variations in working conditions over a long period of time.

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2. Method

In order to tackle this question, the mean spectral distribution of the light received in several locations around the world was first assessed, using long time series of actual measurements of the main atmospheric variables at widely different sites. The locations investigated here were chosen for being representative of the large range of climatic conditions on the planet. They cover a wide range of latitudes (see details in Table 1), extending from Nauru (near the equator) to Palaiseau (near Paris, France). Xianghe (China) is characterized by a high pollution level resulting in systematically large AOD. Nauru is a tropical site with high PW, as opposed to arid sites, such as Sede Boqer. The latter is characterized by intermediate values of all variables, with however large daily excursions in AOD and α in the wake of regional dust storm activity.

The direct normal irradiance spectrum was calculated with SMARTS radiative model (Gueymard, 2001) whose main input parameters are the Air Mass (AM), the Aerosol Optical Depth (AOD), the Precipitable Water (PW), the Angstrom exponent (α),. The AM values were evaluated in SMARTS from the solar zenith angle (Z) for the location and time considered. Simultaneous values of Z, AOD, PW, α, were obtained from the Aerosol Robotic Network (AERONET) database (http://aeronet.gsfc.nasa.gov). From this set of data, the mean annual solar spectra were derived for each selected location, and compared to the AM1.5D (AM=1.5, AOD_{500} = 0.084 and PW = 1.416 cm) solar spectrum (from ASTM G173) commonly used as an input solar spectrum when designing solar cells.

Table 1: Characteristic parameters for the selected locations

Location	Simulated year	Lat. (°)	Long. (°)	Elevation (m)	Mean daily DNI (kWh/m2/day) [Source: (SWERA)]	Annual mean atmospheric parameters AM | AOD | PW |α
Nauru	2011	-0.52	166.92	7	6-6.5	1.72 | 0.09 | 4.17 |0.26
Sede Boqer	2004	30.86	34.78	480	6-6.5	1.92 | 0.18 | 1.34 |0.86
Xianghe	2009	39.75	116.96	32	2.5-3	2.07 | 0.53 | 1.01 |1.12
Palaiseau	2012	48.71	2.21	156	3–3.5	2.29 | 0.16 | 1.44 |1.15

Fig. 1 depicts the spectral distribution of the mean annual solar spectrum for each city investigated in this study, using the method described above. Some spectra are shown to deviate drastically from the AM1.5D Spectrum (bold purple curve). Places characterized by low latitudes and favorable climatic parameters (such as Sede Boqer or Nauru) show relatively high annual mean intensities. Conversely, places characterized by high latitudes (such as Palaiseau) and/or poor atmospheric parameters (i.e Xianghe), demonstrate modest values of the mean annual solar spectrum. Such a representation, however, does not allow a convenient analysis of the extent with which each range of wavelength is altered.

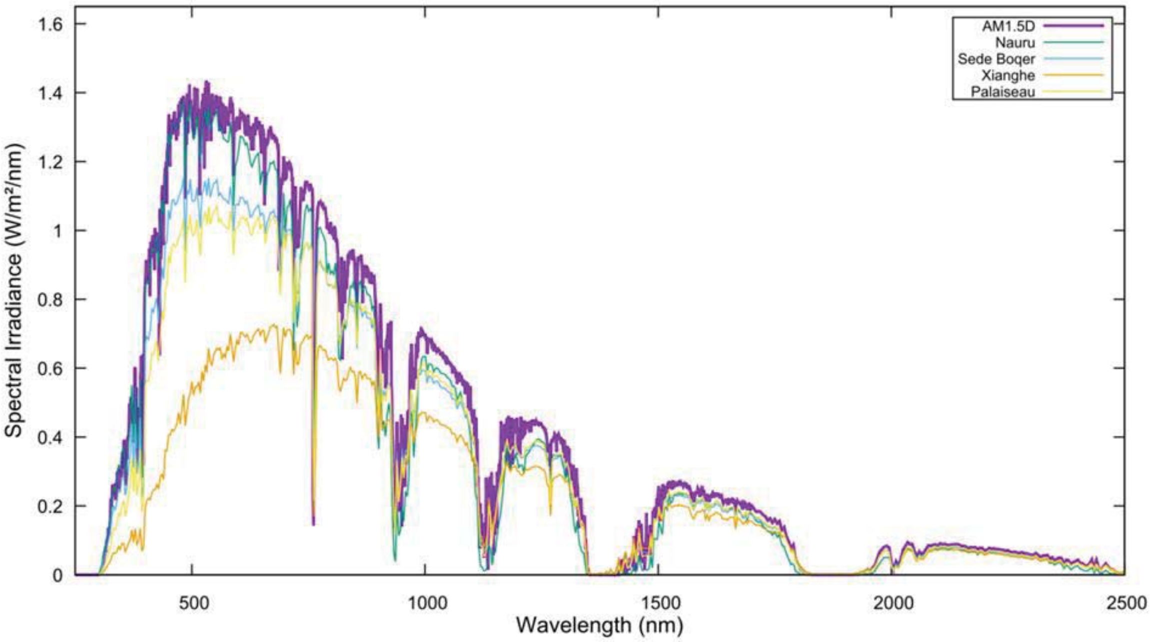

Fig. 1: Mean annual solar spectrum for each investigated city

For sake of clarity, the relative residual of the mean annual spectrum with the AM1.5D spectrum is reported in Figure 2. The spectra are normalized so that the total solar irradiance corresponding to each spectrum equals the power corresponding to AM1.5D solar spectrum (900W/m²). The deviation relative to the AM1.5 solar spectrum is represented as a red curve for each city investigated. The regions of the spectra corresponding to the absorption bands were removed from the graphs (the very low spectral irradiance values associated with these regions gave rise to high levels of noise). Several statements can be drawn from Fig. 2:

- First, for Xianghe and Palaiseau, the mean annual spectrum, calculated using the method described above, shows lower irradiance values in the UV-Vis range relative to the AM1.5D solar spectrum. From these first preliminary data values, it is expected that a fine-tuning of the MJ cells will lead to an optimal combination of subcells characterized by lower values of their electronic gaps, when compared to AM1.5-optimized MJ cells. On the other hand, Nauru exhibits higher values in the UV-Vis range and consequently higher electronics gaps are expected. The solar spectrum is mostly attenuated in this range by the air mass and the AOD which are particularly low in this city. Sede Boqer presents a spectrum similar to AM1.5 and significant differences in the bandgaps are not expected.

- Second, the amplitude of the spectrum alteration over a full year varies drastically from one place to the other. If Nauru and Sede Boker show modest variations in the annual spectral distribution of light (relative to AM1.5 spectrum), Palaiseau and Xianghe demonstrate significant changes in the spectral content of the light, and fine-tuned MJ cells should could lead to a noticeable improvement in the electrical efficiency of CPV systems in these locations.

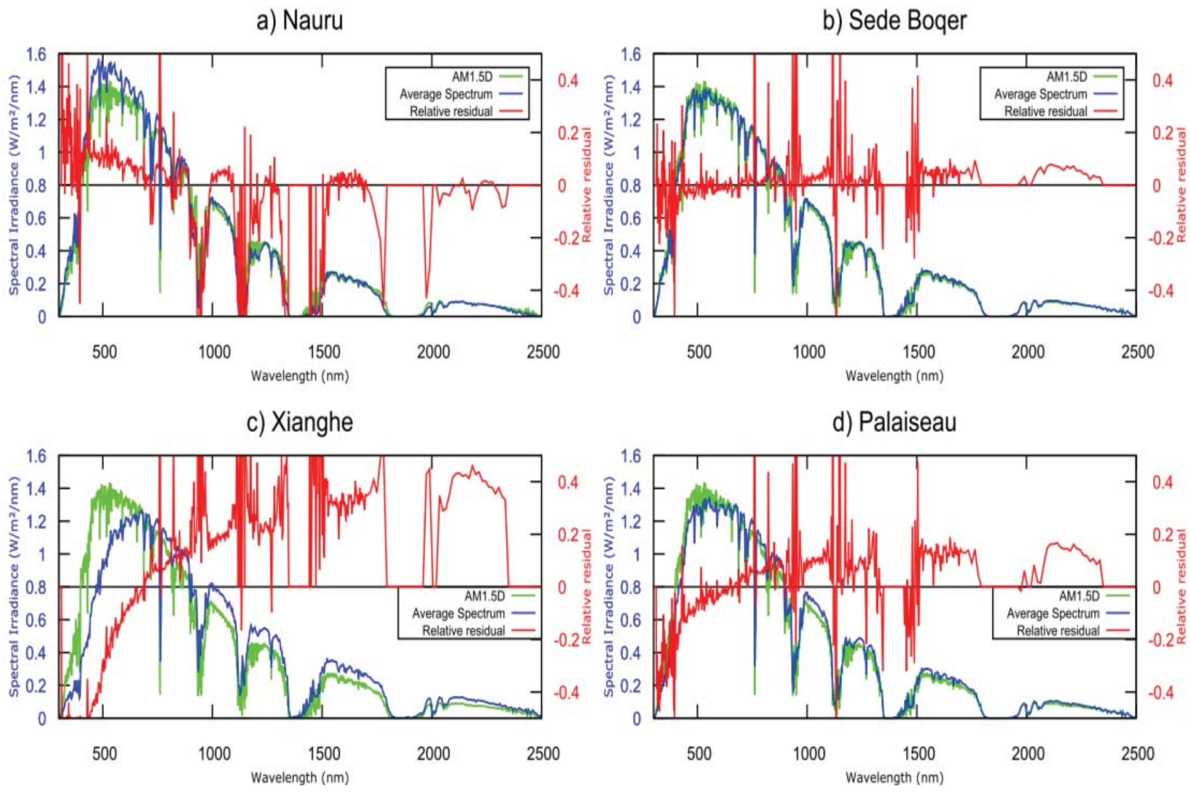

Fig 2: Relative residual of the normalized mean annual spectrum of each city (in red) compared to reference spectrum AM1.5D (in green) and the mean annual spectrum of each city (in blue)

The optimal combination of electronic gaps leading to the highest conversion efficiency was derived using the Shockley and Queisser (SQ) model with the mean annual spectra as an input spectrum for each selected location. The model considers the following assumptions:

- Each absorbed photon generates one single electron-hole pair
- There is no absorption of photons with energy less than the semiconductor band gap
- The only recombination process within the cell is radiative recombination; the other non-radiative processes (SRH, Auger) are thus neglected
- There are no resistive losses
- The cell temperature is kept equal to the ambient temperature (298 K).

The numerical method used here is based on the detailed balance model originally suggested by SQ. The conversion efficiency of these MJ cells was calculated using the detailed balance formalism (Brown and Green, 2002; Vossier et al. 2015) which only requires as an input a reduced set of parameters, namely the sun and the cell temperature, the spectral distribution of the light absorbed, and the electronic gaps of the semi-conductor materials used in the cell.

Basically, the maximum electrical power that can be extracted from a solar cell is obtained as the difference between the absorbed and emitted radiation. Both are conveniently described by the generalized Planck's law, as pointed out in (Brown and Green, 2002).
The maximum current (*I*) extractable from the cell can be obtained from:

$$I/q = \dot{N}_S - \dot{N}_R \quad (1)$$

where q is the elementary charge, and $\dot{N}_S$ and $\dot{N}_R$ are the current contributions associated with the absorption and emission of photons, which both are a function of the semiconductor bandgap, cell and sun temperatures, and other parameters, as described in (Vossier et al. 2015).

Using the SQ limit, the ultimate efficiency is given by:

$$\eta_{SQ} = \frac{\left\{qV\left[\dot{N}_S(\mu=0) - \dot{N}_R(\mu=qV)\right]\right\}_{\max}}{P_{in}} \quad (2)$$

where P_{in} is the incident power.

The optimal combination of electronic gaps leading to the highest solar→electricity conversion efficiency was investigated using a genetic algorithm, taking into account the current-constraint between each subcell (introducing such a constraint imposes the current generated by each individual subcell to be equal).

3. Results

The optimal bandgaps and the corresponding conversion efficiencies for MJ solar cells comprising up to ten subcells under the AM1.5D, 298K and 1 sun were obtained in (Vossier et al., 2015 b), and are reported here as a reference to show how the optimal bandgaps change as a function of the selected spectrum for the optimization (Table 2)

Table 2: Optimum efficiencies for MJ solar cells ten subcells comprising up to ten subcells under the AM1.5D spectrum of every city and 1-sun illumination.

Spectrum	Nb. Cells	E_{g1}	E_{g2}	E_{g3}	E_{g4}	E_{g5}	E_{g6}	E_{g7}	E_{g8}	E_{g9}	E_{g10}	Efficiency (%)
AM1.5D	1	1.14										33.2
	2	1.57	0.94									45.1
	3	1.75	1.18	0.7								50.7
	4	1.94	1.44	1.05	0.7							54.4
	5	2.07	1.61	1.26	0.99	0.7						56.6
	6	2.18	1.74	1.44	1.17	0.95	0.68					58.7
	7	2.27	1.85	1.56	1.33	1.12	0.92	0.7				59.8
	8	2.29	1.88	1.59	1.37	1.16	0.96	0.74	0.5			60.8
	9	2.35	1.96	1.69	1.47	1.26	1.09	0.94	0.74	0.53		61.4
	10	2.41	2.03	1.77	1.56	1.39	1.21	1.05	0.92	0.74	0.55	62

Table 3 summarizes the bandgap combinations for MJ cells optimized considering the mean annual spectra of every location investigated, rather than the AM1.5D reference spectrum.

As mentionned before, Xianghe and Palaiseau present lower bandgaps in the UV-Vis range than those obtained considering the AM1.5D spectrum. These 2 cities are located well above the equator and therefore the AM effect over the UV-Vis range is noticeable. In addition, Xianghe presents high pollution levels and thus even lower irradiance in this particular wavelength range.

The normalized average spectrum for Sede Boqer, depicted in Figure 2, shows negligeable differences compared to the AM1.5D reference spectrum. As a consequence, the optimized combination of bandgaps only shows slight variations relative to the AM1.5-optimized reference case, and fine-tuning would not bring any significant gain in the energy output for this location.

On the other hand, the optimized bandgaps for Nauru are energetically higher than the reference case for almost all the wavelengths considered. Nauru is practically located over the equator and characterized by low pollution levels (low AOD) but, as a tropical city, presents high PW. The water vapor absorption bands are mainly located in the near-infrared and infrared regions of the spectrum, accounting for the relative residual drops which can be seen in Figure 2 at around 940, 1100 and 1400 nm. Since the irradiance in the UV-Vis region is higher, the bandgap energies tend to be higher to enhance the conversion for these photon frequencies.

Table 3: Optimum efficiencies for MJ solar cells comprising up to ten subcells under the average spectrum of every city and 1-sun illumination.

Spectrum	Nb. Cells	E_{g1}	E_{g2}	E_{g3}	E_{g4}	E_{g5}	E_{g6}	E_{g7}	E_{g8}	E_{g9}	E_{g10}
Sede Boqer	**1**	1.14									
	2	1.57	0.94								
	3	1.74	1.18	0.71							
	4	1.93	1.45	1.06	0.70						
	5	2.07	1.61	1.26	0.99	0.70					
	6	2.19	1.75	1.45	1.19	0.96	0.70				
	7	2.27	1.86	1.57	1.35	1.13	0.93	0.71			
	8	2.29	1.88	1.59	1.37	1.16	0.97	0.75	0.52		
	9	2.35	1.97	1.69	1.48	1.26	1.10	0.95	0.74	0.53	
	10	2.42	2.03	1.77	1.57	1.40	1.22	1.05	0.93	0.74	0.55
Xianghe	**1**	1.12									
	2	1.34	0.72								
	3	1.59	1.12	0.71							
	4	1.74	1.31	0.99	0.70						
	5	1.81	1.41	1.12	0.80	0.54					
	6	1.94	1.57	1.31	1.11	0.92	0.71				
	7	1.97	1.60	1.35	1.14	0.94	0.73	0.52			
	8	2.03	1.69	1.44	1.24	1.06	0.91	0.74	0.55		
	9	2.11	1.77	1.54	1.37	1.20	1.04	0.89	0.74	0.55	
	10	2.13	1.81	1.58	1.41	1.23	1.09	0.96	0.79	0.69	0.52
Nauru	**1**	1.38									
	2	1.63	0.94								
	3	1.90	1.36	0.79							
	4	2.01	1.51	1.12	0.71						
	5	2.15	1.68	1.34	1.00	0.69					
	6	2.26	1.83	1.51	1.22	0.98	0.71				
	7	2.32	1.91	1.62	1.39	1.16	0.94	0.70			
	8	2.35	1.94	1.66	1.42	1.19	0.98	0.75	0.51		
	9	2.40	2.01	1.75	1.53	1.32	1.15	0.96	0.75	0.54	
	10	2.44	2.08	1.82	1.62	1.44	1.24	1.08	0.94	0.74	0.53
Palaiseau	**1**	1.13									
	2	1.54	0.94								
	3	1.69	1.16	0.70							
	4	1.91	1.45	1.12	0.74						
	5	2.06	1.63	1.33	1.04	0.75					
	6	2.10	1.68	1.40	1.15	0.93	0.69				
	7	2.22	1.82	1.55	1.33	1.14	0.94	0.71			
	8	2.25	1.85	1.58	1.37	1.17	0.98	0.76	0.53		
	9	2.32	1.94	1.69	1.49	1.31	1.16	1.00	0.80	0.69	
	10	2.32	1.94	1.70	1.50	1.33	1.17	1.01	0.81	0.70	0.51

The conversion efficiency for the MJ solar cell architectures reported in the previous Table 3 and for the corresponding annual mean spectrum are depicted together with the efficiency under the same spectrum but using the gaps optimized for AM1.5D in Figure 3.

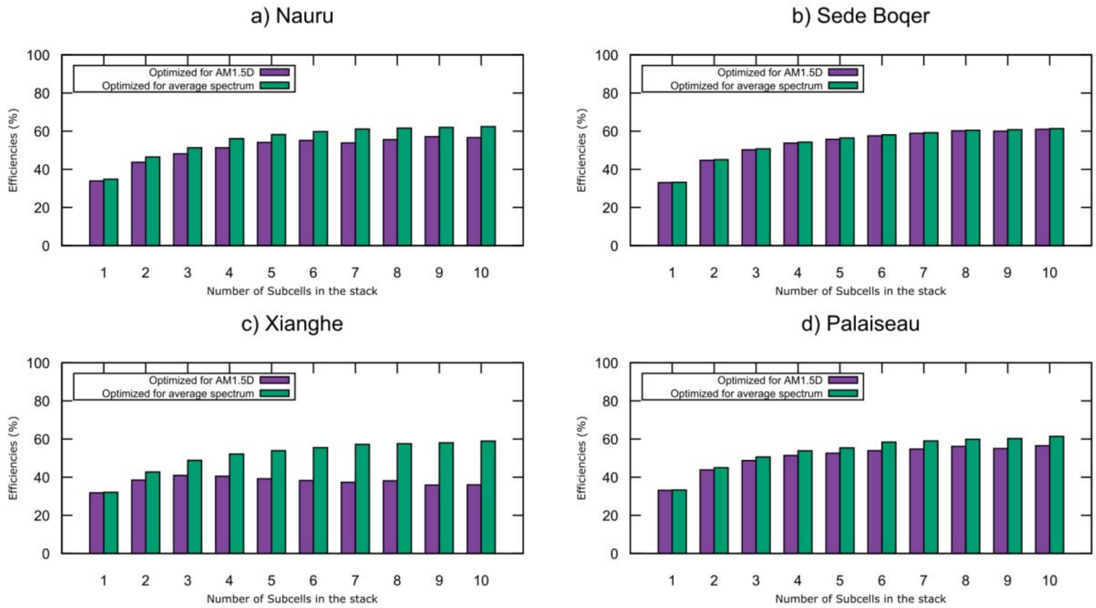

Fig 3: Efficiencies for MJ solar cells comprising up to 10 subcells with gaps optimized for AM1.5D (pink bars) or for average spectrum in every city (green bars)

Fig. 3 illustrates the potential benefits for fine-tuning in different locations around the world: some noticeable improvement in the conversion efficiency can be obtained with fine-tuned MJ solar cells, relative to the “reference” conversion efficiency achieved with AM1.5-optimized cells. However the extent to which fine-tuning may lead to noticeable improvement in the cell efficiency largely depends on the location. The benefit for fine-tuning is particularly strong in Xianghe: because of the noticeable alteration in the spectral distribution of light relative to the reference AM1.5 spectrum, fine-tuning is shown to lead to significant improvement in the cell efficiency, in particular for cell architectures involving a high number of subcells. Nauru and Palaiseau show a modest improvement in the cell efficiency with fine-tuned solar cells, as a result of the minor difference between the mean annual spectral distribution of light and AM1.5 reference spectrum. Finally, the gain in efficiency for fine-tuned solar cells appears to be very weak in Sede Boqer, the mean annual distribution of light and AM1.5 solar spectrum being very close. It should be finally stressed that all the selected locations tend to achieve maximum efficiencies around 60% for the 10 subcells stack, suggesting that fine-tuning of solar cell is a promising way to achieve ultra-high conversion efficiencies for a broad range of climatic and atmospheric conditions.

It was previsouly shown that the higher the number of subcells in the stack, the narrower the range of spectral characteristics for which the cells performs optimally (Vossier et al, 2016). To better grasp the spectral dependence of MJ cells as the number of subcells increases, the relative residual between the optimized and non-optimized efficiencies in the case of Xianghe is plotted in Figure 4 (see Eq. (3)). The relative residual grows sharply with increasing number of subcells, underlining the strong impact of AOD and the fundamental inability of MJ solar cells comprising more than 3 subcells to accommodate spectral variations. The relative residual is higher than 20% with more than 3 junctions and reaches 60% for 10 junctions. Thus, the benefit for tailoring the gaps in this specific case could lead to an efficiency increase of 60% with 10 gaps.

$$Relative\ residual(\%) = 100\left(\frac{Efficiency\ for\ the\ optimized\ gaps - Efficiency\ for\ the\ AM1.5D\ gaps}{Efficiency\ for\ the\ AM1.5D\ gaps}\right) \quad (3)$$

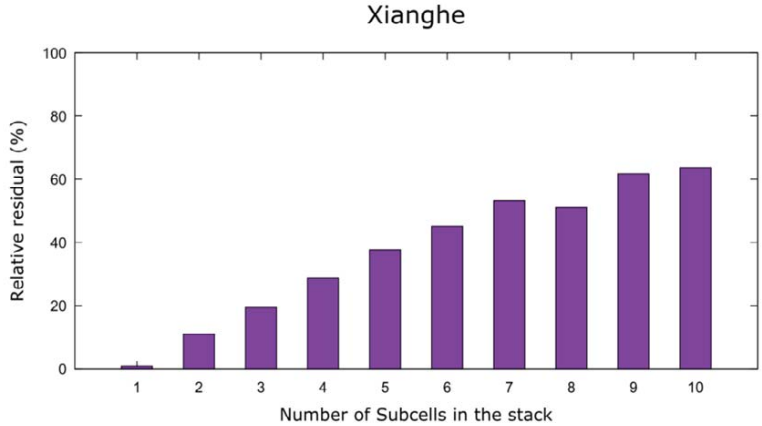

Fig 4: Efficiency relative residual in the case of Xianghe

4. Conclusions

Fine-tuning of solar cells can potentially increase the efficiency with which solar energy is converted into electricity, by tailoring the combination of electronic gaps to the spectral distribution characteristic of a particular location. The present results suggest that increasing the number of subcells in a MJ stack leads to increased conversion efficiency. However, locations characterized by a strong alteration in the mean annual spectral distribution relative to AM1.5 solar spectrum only show modest improvement in the maximum conversion efficiency achievable, when designing the cells using AM1.5 as a reference spectrum. In this work, we showed that fine-tuning of MJ solar cells may allow a significant increase in the cell conversion efficiency. The amplitude of the efficiency gain associated with fine-tuning largely depends on the variation in the mean distribution of light relative to AM1.5 spectrum. Locations characterized by minor difference in the spectral distribution of the light (relative to AM1.5) show a very weak improvement in the conversion efficiency of fine-tuned MJ solar cells. Conversely, locations characterized by a noticeable modification in the spectral distribution of light demonstrate a strong improvement in the efficiency of fine-tuned MJ cells. Finally, it was demonstrated that the maximum conversion efficiency achievable with fine-tuned MJ cells is around 60% for the 10 subcells stack, suggesting that this approach is a promising way to achieve ultra-high conversion efficiencies for a broad range of climatic and atmospheric conditions.

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