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The effect of the recombination mechanisms location on the temperature sensitivity of thin-film photovoltaic cells

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Abstract. Thin film solar cells temperature sensitivity and impact of the main recombination mechanism location are investigated in this paper. The main mechanisms in bulk and at the heterojunction interface are discriminated. Using a 1D simulation software, “Solar Cell Capacitance Simulator” (SCAPS), we observed a higher temperature coefficient of open circuit voltage (V_{oc}) for cells with main recombination centers at the interface than the one with main recombination centers in volume. Furthermore, an LTSpice module model is used to visualize the effects of the recombination centers’ location on the performance ratios of the modules. The results show more degradation for the ratios performance of cells with the main recombination mechanisms at the interface than those in volume.

Keywords: Temperature sensitivity / recombination mechanisms / ratios performance / thin film cells

1 Introduction

The weighted average cost of installed solar photovoltaic electricity dropped from \$5 /Watt in 2009 to about \$2 /Watt in 2015 [1]. This drop in cost helps to show that the new main challenge in this domain is to ensure the efficient operation of networks. In Africa, numerous projects are implemented for both large scale PV plants and stand-alone PV systems. However, in order to obtain a sustainable and reliable modules operation, the local climatic conditions should be taken into account. Temperature and dust are one of the climatic factors that significantly influence the performance of solar modules [2,3]. These two factors characterize most of sub-Saharan African countries. Even if the effect of dust can be eliminated by programmed cleaning, the reduction of the temperature impact depends on the solar cell quality. In an early work, Green studied the temperature sensitivity of photovoltaic cells [4]. He derived the general form of the temperature coefficient of the open circuit voltage (V_{oc}) of the PV cells. This coefficient depends on recombination mechanism in the cells. His findings have been refined for the case of radiative

recombination in cells by Dupré [5]. Thin film solar cells can exhibit a higher defect density at the heterojunction interface than in the bulk of each junction layer due to lattice mismatch and defect segregation at the interface.

We examine the main recombination mechanisms location impact on the V_{oc} temperature coefficient of thin film cells. Different thin film solar cells configurations with three technologies (copper indium gallium selenide (CIGS), Perovskite, silicon tandem) are investigated. We have gone one step further and checked over these cells’ performance ratios in sub-Saharan African climatic conditions. The results are compared to the most used cell technology (crystalline silicon).

2 Materials and methods

Figure 1 summarizes the approach used in this study. The numerical simulations are performed using the 1D simulation software named “Solar Cell Capacitance Simulator” (SCAPS ver. 3.3.02). The solar cell architectures defined consist of transparent conductive oxide/buffer/absorber/transport material. The basic physics and device parameters for the simulated cells are obtained from literature [6–8]. The parameters for cells heterojunction layers are summarized in Table 1. In order to

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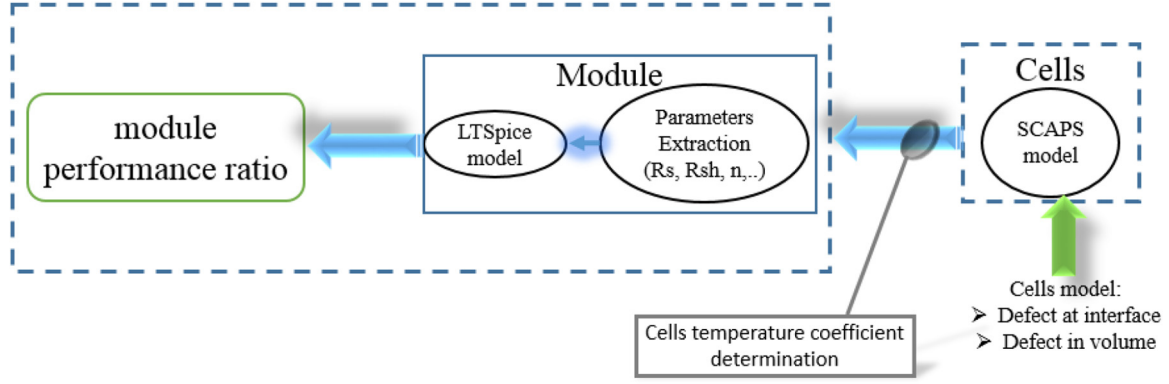


Fig. 1. Summary of the study approach.

Table 1. Parameters of the layers forming the heterojunction for each cell.

Cells	Tandem-Si			CIGS		Perovskite		
Layers	a-Si:H (i)	$\mu\text{c-Si}$ (n)	a-Si:H (i)	CIGS	CdS	TiO ₂	Perovskite	Spiro-HTM
Parameters								
d (μm)	0.01	200	0.01	1	0.1	0.05	0.323	0.350
E_g (μm)	1.72	1.15	1.72	1.2	2.4	3.2	1.55	3
χ	3.9	4	3.9	4.1	4	3.9	3.9	2.45
ε	11.9	11	11.9	10	10	9	6.5	3
N_c (cm^{-3})	10^{20}	2.8×10^{19}	10^{20}	10^{19}	10^{19}	2.2×10^{18}	2.2×10^{18}	2.2×10^{18}
N_v (cm^{-3})	10^{20}	10^{19}	10^{20}	10^{19}	10^{19}	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}
$(\text{cm} \cdot \text{s}^{-1})v_{thn}$	10^7	10^7	10^7	10^7	10^7	10^7	10^7	10^7
$(\text{cm} \cdot \text{s}^{-1})v_{thp}$	10^7	10^7	10^7	10^7	10^7	10^7	10^7	10^7
$(\text{cm}^2 \cdot \text{s}^{-1})\mu_n$	20	816	20	25	50	5	2	2×10^{-4}
$(\text{cm}^2 \cdot \text{s}^{-1})\mu_p$	5	480	5	10	25	5	2	2×10^{-4}
N_d	10^{14}	5×10^{16}	10^{14}	–	5×10^{17}	2×10^{19}	10^{13}	–
N_a	10^{14}	–	10^{14}	4×10^{16}	–	–	10^{13}	2×10^{18}

analyze main recombination center's location influence on the cells temperature sensitivity, two types of structures have been modeled for each cell:

- a structure without interface states at the solar cell's junction. The main recombination centers are located in the bulk;
- a structure representing a solar cell with interface state at the junction. For these cells, the recombination mechanism at the interface dominates those in volume.

Defects energy distribution are introduced by two Gaussian for the a-Si:H (i)/ $\mu\text{c-Si}$ (n) and $\mu\text{c-Si}$ (n)/a-Si:H (i) hetero-junction. For the case of CIGS (p)/CdS(n), TiO₂/Perovskite or Perovskite/Spiro-HTM interfaces, uniform donor defects energy distribution is used. The typical recombination mechanism in thin film solar cells is

Shockley–Read–Hall (SRH) one [9,10]. This mechanism is used for the device simulation in SCAPS by entering the defect density (N_d). The SRH recombination rate (R_{SRH}) is given by the following equation:

$$R_{\text{SRH}} = \frac{(np - n_i^2)}{\tau_{p0} \left[n + n_i \exp\left(\frac{E_d - E_i}{k_B T}\right) \right] + \tau_{n0} \left[p + n_i \exp\left(\frac{E_i - E_d}{k_B T}\right) \right]} \quad (1)$$

where

$$\tau_{n0} = \frac{1}{\sigma_n v_{th} N_d} \text{ and } \tau_{p0} = \frac{1}{\sigma_p v_{th} N_d}$$

depend on thermal velocity (v_{th}), defect density (N_d) located at energy E_d and capture cross section ($\sigma_{n,p}$). n, p are electron, hole concentrations, respectively and n_i the intrinsic charge carriers concentration.

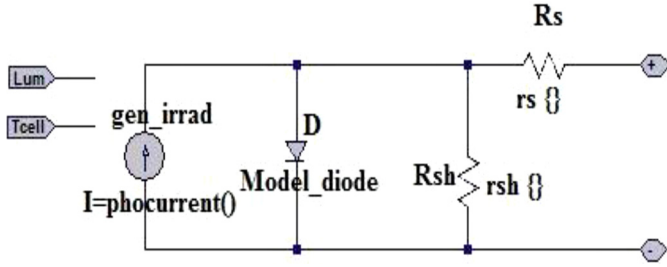


Fig. 2. LTSpice model.

In this work, we also consider the contribution of the recombination mechanism to the reduction of the PV cells performance. The defect density is considered as a variable parameter during the simulation in order to have cells with different efficiencies. However, due to the cell's specificity, the defect density introduced to have the same efficiency for different cells is different.

Furthermore, the performance ratios of the modeled cells were evaluated according to the location of the main recombination centers and compared to those of crystalline silicon-based technologies. We use for this purpose, the LTSpice model of modules (Fig. 2) where $r_s\{\}$ and $r_{sh}\{\}$ are the parametric values of R_s and R_{sh} , respectively. The mathematical model used is given by equation (2). The input variables are cell's electrical parameters (series (R_s) and shunt (R_{sh}) resistances, ideality factor (n), and saturation current (I_0), *Standard Test Conditions* and climatic data (ambient temperature, irradiation and wind speed). The influence of sub-Saharan African climatic conditions on solar module has been studied by Kata et al. [11]. The module electrical parameters are obtained from the hybrid algorithm based on analytical and Levenberg-Marquardt algorithms that we developed and validated [12] (Fig. 3). The temperature and sun irradiation used for simulation were measured in real condition (sub-Saharan condition) at the same time by temperature sensor PT100 and a pyranometer.

$$I = I_{ph} - I_0 \left[\exp\left(\frac{qV}{nK_B T}\right) - 1 \right] - \frac{V + R_s I}{R_{sh}} \quad (2)$$

$$I_{oin} = \frac{I_{phin} - \frac{V_{ocref}}{R_{shin}}}{\exp\left(\frac{qV_{ocref}}{nK_B T_{ref}}\right) - 1} \quad (3)$$

$$R_{shin} = \frac{(V_{mref} + I_{mref} R_{sref})}{I_{phin} - I_{mref} - I_{oin} \left(\exp\left(\frac{q(V_{mref} + I_{mref} R_{sin})}{nK_B T_{ref}}\right) - 1 \right)} \quad (4)$$

$$R_{sin} = R_{soin} - \frac{1}{\frac{q}{nK_B T_{ref}} I_{oin} \exp\left(\frac{qV_{ocref}}{nK_B T_{ref}}\right)} \quad (5)$$

$$I_{phin} = \frac{R_{sin} + R_{shin}}{R_{shin}} I_{scref} \quad (6)$$

$$R_{soin} = \frac{V_{ocref} - V_{mref}}{2I_{mref}} \quad (7)$$

$$R_{shoin} = \frac{V_{mref}}{I_{scref} - I_{mref}} \quad (8)$$

where K_B is the Boltzmann constant, q is the charge of electron, R_{sin} is the initial series resistance, R_{shin} is the initial shunt resistance, R_{soin} is the reciprocal slope of initial I - V curve at open-circuit condition, I_{phin} is the initial photo-generated current, I_{oin} is the initial dark saturation current, V_{ocref} is the reference open circuit voltage, V_{mref} is the reference maximum output voltage, I_{mref} is the reference maximum output current, I_{scref} is the reference short circuit current and T_{ref} (25 °C).

3 Results and discussion

The temperature variation leads to a slight increase in the short-circuit current (I_{sc}) while the open circuit voltage (V_{oc}) is much more affected by this variation. Therefore, knowing the cell V_{oc} temperature sensitivity, one can evaluate the cell's temperature sensitivity. At the open circuit, generated currents and recombination currents are balanced. The open circuit voltage of the cell is written as [13]:

$$V_{oc} = \frac{nK_B T}{q} \ln\left(\frac{I_{sc}\eta(V_{oc})}{I_0}\right) \quad (9)$$

where $I_0 = I_{00} e^{E_a/nkT}$ and E_a , activation energy.

We assume a linear variation of E_a in cell operating temperature range:

$$E_a = E_{a0} + T \frac{dE_a}{dT}. \quad (10)$$

Differentiating equation (9) gives equation (11) similar to that obtained in reference [5]:

$$\frac{dV_{oc}}{dT} = -\frac{\frac{E_{a0}}{q} - V_{oc} + \zeta \frac{nK_B T}{q}}{T} \quad (11)$$

$$\zeta = \frac{d\ln(I_{sc})}{d\ln T} + \frac{d\ln(\eta(V_{oc}))}{d\ln T} - \frac{d\ln(I_{00})}{d\ln T}.$$

E_{a0} and V_{oc} depend on the location of the recombination mechanism. Figures 4a–4c show that the cell junction activation energy depends on the location of the recombination mechanism:

– If the main recombination centers are located at the junction's interface and the band off-set (ΔE_c) is less than zero (cliff), then

$$E_a = \min(E_{g1}, E_{g2}) + \Delta E_c. \quad (12)$$

E_{g1} and E_{g2} are the band gaps of the semiconductors forming the cell's junction. Due to a negative conduction band offset, the value of electron energy at interface and thus the electron concentration at the interface is increased.

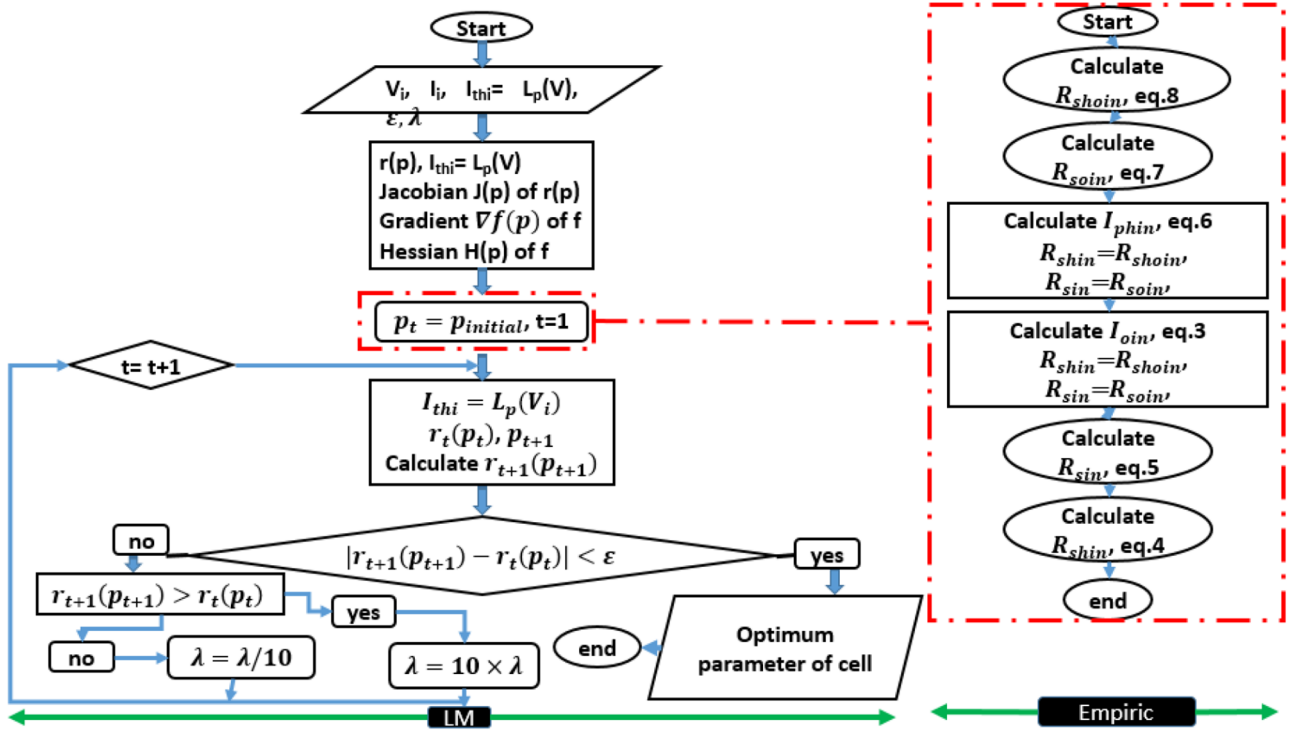


Fig. 3. Organigram of the cell parameters extracting program.

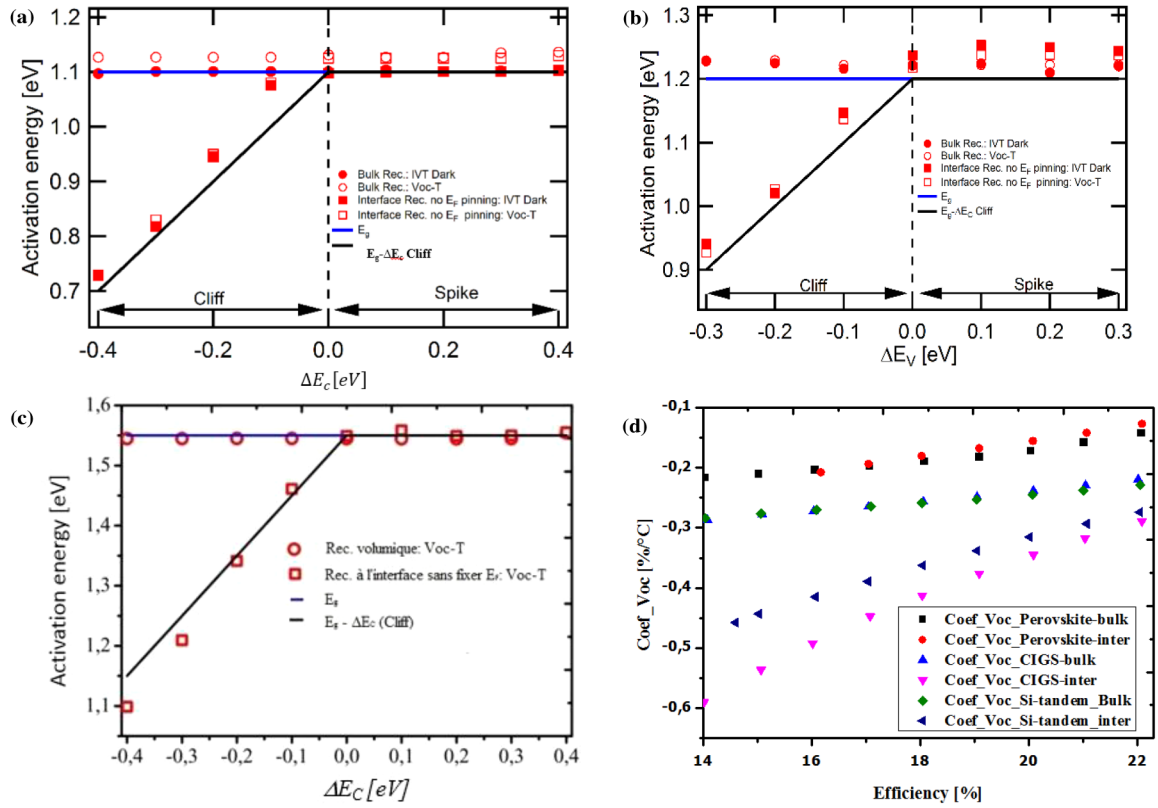


Fig. 4. The summary of the results of the energy of the two methods for activating the tandem amorphous/microcrystalline (a), CIGS (b) and Perovskite (c) and (d) variation of the open circuit voltage temperature coefficient as a function of efficiency.

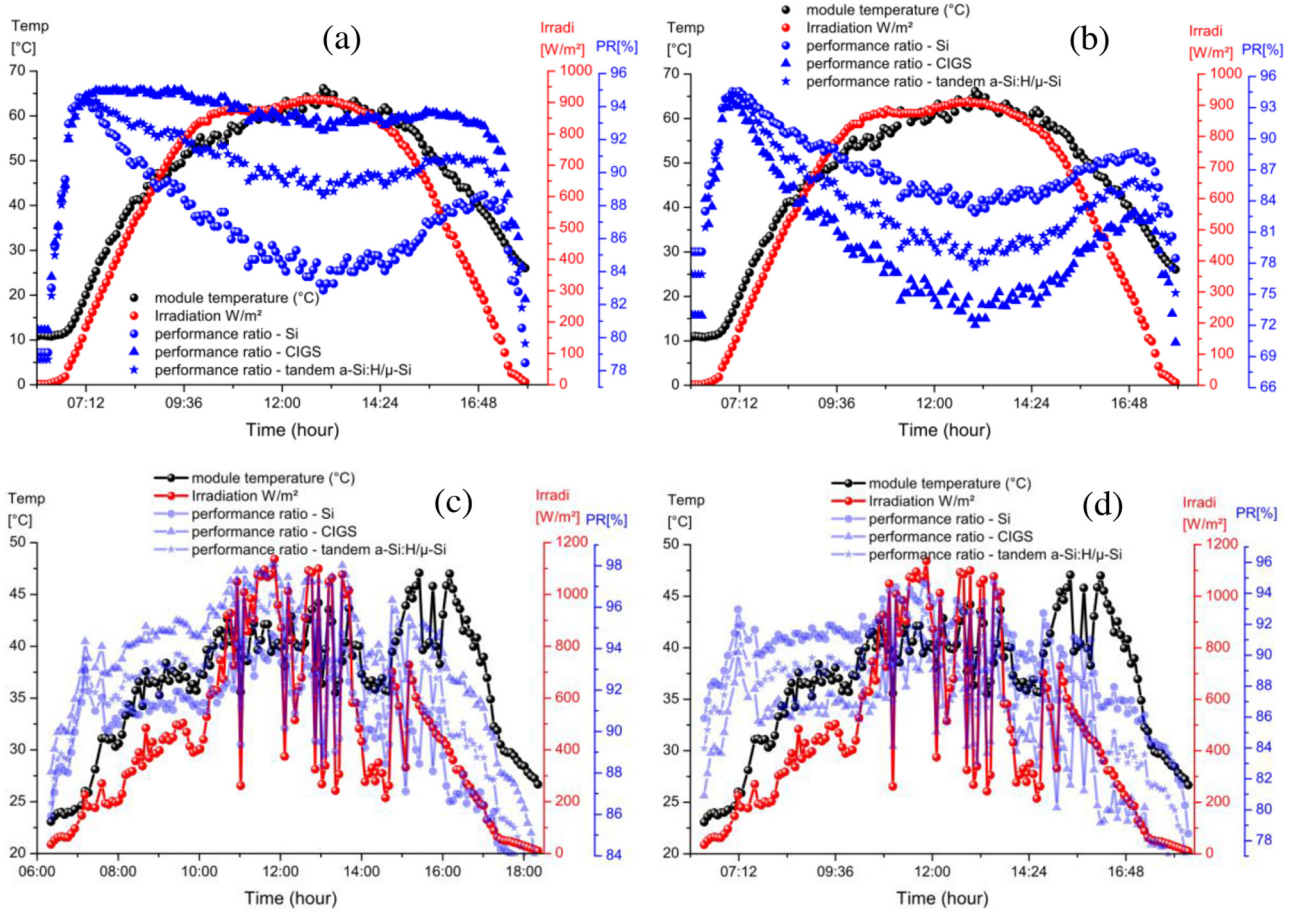


Fig. 5. Daily evolution of the PR of different photovoltaic modules with: main recombinant centers in volume for a clear day (a) and cloudy day (c), main recombinant centers at the interface for a clear day (b) and cloudy day (d).

– Otherwise, if the main recombination centers are located in the volume of the absorber or the band off-set (ΔE_c) is upper than zero (spike), then

$$E_a = \min(E_{g1}, E_{g2}). \quad (13)$$

Sheer [13] derived the same valuable rules for activation energy.

Figure 4d presents cells' open circuit voltages temperature coefficient as a function of efficiency (defect density).

As mentioned elsewhere [5], the temperature coefficient of the open circuit voltage is explicitly sensitive to the recombination's mechanism. Among the simulated cells (Fig. 4), the perovskite one is less sensitive to temperature variations regardless of the location of the recombination centers. The CIGS and silicon tandem cells are not only relatively sensitive to temperature variation but also this sensitivity becomes more important when the recombination centers are located at the interface of the cell. Their efficiencies are low for the higher density of recombination centers. Due to lattice mismatch or defect segregation of cell's layers, the thin film solar cells present a high risk of the presence of the recombination center at their interface junction. So, reducing defect density at the thin films solar cells interface would contribute in reducing their temperature sensitivity.

Even if, perovskite is interested in photovoltaics, very few modules based on this cell technology have been tested in outdoor conditions [14]. Due to the non-maturity of the perovskite technology, their modules will not be studied in the rest of this work.

The performance ratios (PR) of the different modules under conditions of a cloudy day with cell temperatures below 50 °C and a clear sky day with temperatures around 70 °C are simulated. The different modules were simulated for cells with 18% of efficiency. The results are shown in Figure 5. This performance indicator is given by equation (14).

$$PR = \frac{P_{mp}}{P_{mp,STC}} \times \frac{I_{sc,STC}}{I_{sc}}. \quad (14)$$

The performance ratios are much lower for modules with main recombination centers at the interface of their cells. Otherwise, the thin film (tandem and CIGS) modules with main recombination centers in the volume of their cells lose performance less quickly compared to those with recombination at the interface. For the same efficiency, crystalline silicon module performance ratios become higher than thin film module with recombination at the cells interface.

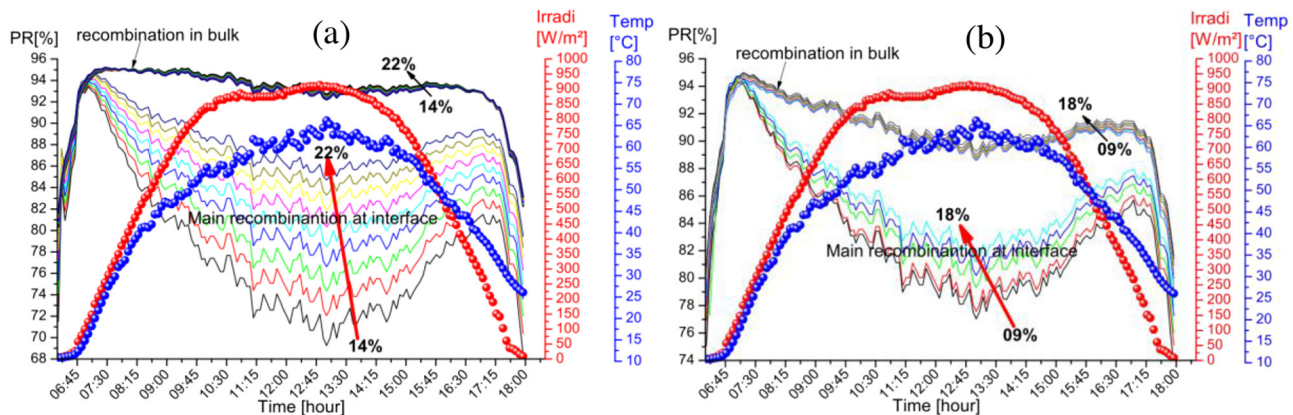


Fig. 6. Performance ratio of different efficiency of CIGS modules (a) and silicon tandem (b).

The results of Figure 6 show that the performance ratios of the thin film cells with main recombination mechanisms at the heterojunction interface are more degraded. This figure further illustrates the importance of defect reduction at the interface of the thin film solar cell junction.

4 Conclusion

We have shown that the location of the main recombinant mechanisms impacts on cell temperature sensitivity. Among the simulated cells, the Perovskite cell is less sensitive to temperature variation. Although thin film cells have good performance ratios compared to crystalline silicon with the same efficiency, these performances drop quickly when their heterojunction interface have the main recombination centers. Thus, ensuring a good quality of the junction of thin film cells will contribute to the reduction of the temperature sensitivity of these cells.

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Author contribution statement

This paper is result of a research done in LEITER laboratory by N. Kata, a member of LEITER. The data analysis is done by N. Kata under the supervision of D. Diouf and A. Darga. Professor A. Seïdou Maïga is the director of laboratory and oversaw the entire study of the paper.

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